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Pharmacy Students' Experiences of Learning in the Laboratory

PhD Thesis by Laura Teinholt Finne

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Laura Teinholt Finne
Department of Pharmacy
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Principal Supervisor: Bente Gammelgaard
Co-Supervisor: Frederik Voetmann Christiansen
Co-Supervisor: Jan Alexis Nielsen

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Summary

The laboratory is a crucial environment for teaching and learning in university-level science education. Pharmaceutical sciences, including chemistry, heavily rely on the laboratory for discipline-specific learning activities and outcomes. The laboratory is a multifaceted learning environment where numerous factors influence student learning. Through this thesis, I aim to contribute to the comprehension of students' experiences in the teaching laboratory to enhance laboratory teaching and learning. I seek to understand what students in the chemical sciences learn from their laboratory experiences and which factors shape their experience of learning.

By conducting a systematic review of the empirical literature on students' outcomes resulting from laboratory experiences, I outline the intricate nature of the laboratory environment by exploring various multimodal and diverse student learning outcomes. The review identifies five clusters of laboratory-related outcomes: experimental competence, disciplinary learning, higher-order thinking and epistemic learning, transversal competence, and affective outcomes.

In my empirical study of students' laboratory experiences, I conducted in-depth semi-structured interviews with pharmacy students at the University of Copenhagen. Through a phenomenographic analysis of these interviews, I describe students' perceptions of time and the theory-practice relationship within the laboratory. Some interviews focused on students' experiences during the lockdown of universities due to COVID-19. This analysis focuses on the students' experiences of the lab in its absence. Thematic analysis was more suitable than phenomenography due to the considerable similarities among the students' experiences.

Regarding students' experience of time, I illustrate its influential role in the students' perception of congruence within the laboratory. I show the importance of witnessing the transformations that occur in the laboratory as a prerequisite for developing scientific judgment. In addition, embodied experiences in the laboratory and face-to-face discussions and feedback with teachers emerge as significant aspects of the laboratory learning experience. Lastly, I explore how students perceive the laboratory's role in bridging theory and practice. While some students actively utilise the laboratory experience to comprehend the interplay between theory and practice, others perceive the laboratory as a mere representation of theoretical concepts.

With this PhD thesis, I contribute to understanding laboratory teaching and learning within pharmacy and chemistry education. This research contributes to the ongoing discourse on enhancing the quality and effectiveness of laboratory education in these disciplines.

Resumé

Laboratoriet spiller en afgørende rolle som lærings- og undervisningsmiljø på videregående naturvidenskabelige uddannelser. Især inden for kemi og farmaceutisk videnskab er laboratorieundervisning en omfattende del af uddannelsen og giver mulighed for disciplin-specifikke undervisningsformer og læringsudbytter. Laboratoriet er et komplekst læringsmiljø, hvor talrige faktorer påvirker studerendes læring. Gennem denne afhandling sigter jeg mod at bidrage til forståelsen af studerendes oplevelser i undervisningslaboratoriet med det ultimative mål at forbedre laboratorieundervisning og læring.

Gennem et systematisk review af empirisk litteratur om studerendes læringsudbytter fra laboratorieundervisningen beskriver jeg laboratoriets komplekse karakter ved at udfolde dets multimodale natur og de mange forskelligartede læringsudbytter hos de studerende. Reviewet identificerer fem clusters af laboratorierelaterede kompetencer: eksperimentel kompetence, konceptuel faglig læring, højere-ordens udbytter og epistemisk læring, generelle kompetencer og affektive påvirkninger.

Igennem mit empiriske arbejde med studerendes faktiske laboratorieoplevelser gennemførte jeg dybdegående semi-strukturerede interviews med farmaceutstuderende på Københavns Universitet. Gennem en fænomenografisk analyse af disse interviews beskriver jeg studerendes opfattelser af tid og forholdet mellem teori og praksis i laboratoriet. Nogle interviews fokuserede på studerendes oplevelser under nedlukningen af universiteterne på grund af COVID-19. Denne analyse fokuserer på oplevelsen af laboratoriet i fraværet af netop dette. Tematisk analyse viste sig at være mere egnet end fænomenografisk analyse grundet iøjnefaldende ligheder i de studerendes oplevelser.

Når det kommer til studerendes oplevelse af tid, illustrerer jeg tidens indflydelsesrige rolle for deres opfattelse af sammenhæng i laboratoriet. Desuden lægger jeg vægt på vigtigheden af at iagttage de transformationer, der finder sted i laboratoriet, som en forudsætning for at udvikle videnskabelig dømmekraft. Derudover fremhæver jeg betydningen af kropslige oplevelser i laboratoriet samt face-to-face-diskussioner og feedback fra undervisere som væsentlige aspekter af laboratorie-læringsoplevelsen. Til sidst udforsker jeg de forskellige måder, hvorpå studerende opfatter laboratoriets rolle med hensyn til at binde teori og praksis sammen. Mens nogle studerende aktivt udnytter laboratorieoplevelsen for at forstå samspillet mellem teori og praksis, betragter andre laboratoriet som en ren repræsentation af teoretiske koncepter.

The thesis is based on the following four published papers, referred to as papers 1-4 throughout the thesis.

Paper 1
Agustian, H. Y., Finne, L. T., Jørgensen, J. T., Pedersen, M. I., Christiansen, F. V., Gammelgaard, B., & Nielsen, J. A. (2022). Learning outcomes of university chemistry teaching in laboratories: A systematic review of the empirical literature. *Review of Education*, 10, e3360. https://doi.org/10.1002/rev3.3360

Paper 2
Finne, L. T., Gammelgaard, B., & Christiansen, F. V. (2021). Tid til læring i laboratoriet: farmaceutstuderendes opfattelse af tiden i laboratorieundervisningen. *Dansk Universitetspædagogisk Tidsskrift*, *16*(30), 43-58 https://tidsskrift.dk/dut/article/view/121856/172530.

This publication is in Danish but is published here in translation.

Paper 3
Finne, L. T., Gammelgaard, B., & Christiansen, F. V. (2022). When the Lab Work Disappears: Students' Perception of Laboratory Teaching for Quality Learning. *Journal of Chemical Education*, *99*(4), 1766-1774. https://doi.org/10.1021/acs.jchemed.1c01113

Paper 4
Finne, L. T., Gammelgaard, B., & Christiansen, F. V. (2022). Pharmacy students' conceptions of theory-practice relation in the analytical chemistry laboratory – a phenomenographic study. *Chemistry Education Research and Practice* 2023, **24**, 428 - 436. https://doi.org/10.1039/d2rp00092j

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In addition, I have contributed to a paper not included in the thesis for assessment. Although specific findings from this study are relevant to my thesis, I have chosen not to include them because my thesis specifically focuses on the students' perspectives on laboratory experiences, while the paper in question, Paper 5, centres on the teachers' perspectives. Besides, my contribution to this paper was relatively minor compared to the other papers I have included for assessment.

Paper 5
Agustian, H. Y., Pedersen, M. I., Finne, L. T., Jørgensen, J. T., Nielsen, J. A., & Gammelgaard, B. (2022). Danish University Faculty Perspectives on Student Learning Outcomes in the Teaching Laboratories of a Pharmaceutical Sciences Education. *Journal of Chemical Education*. https://doi.org/10.1021/acs.jchemed.2c00212
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Contents

1– Introduction

The laboratory setting holds immense potential for science education, allowing students to develop their scientific thinking and judgment while gaining a deeper understanding of content and essential competences (Hofstein, 2017). In pharmaceutical sciences, laboratory work is a crucial curriculum component, occupying a considerable portion of students' weekly schedules.

However, despite the significant role of laboratory teaching in higher education, there is still uncertainty regarding the learning outcomes that students derive from these experiences. Teachers acknowledge the importance of laboratory work for theories to come alive in practice and for students to acquire vital competences. Yet, many teachers struggle realising these potentials (Petersen, 2015; Wynns, 2015). These challenges have persisted for years, as evidenced by science education research (Hofstein, 2017).

Several challenges persist in laboratory teaching within higher education science curricula, including unclear learning goals for laboratory work leading to discrepancies between students' understanding and teachers' expectations (Reid & Shah, 2007, Tamir, 1989). Students also tend to prioritise following instructions over grasping underlying concepts (Nakhleh, 1994) and focus on completing exercises rather than seeking deep learning (Meester & Maskill, 1995). These long-standing issues, identified in science education research, continue to hinder the realisation of the full potential of laboratory teaching.

Laboratory courses are essential for high-quality learning in biochemical sciences (Mccune & Hounsell, 2005). However, this analysis was not based on empirical data from laboratory courses but on interviews with students in other settings. The focus of this thesis is laboratory courses. How they contribute to learning is primarily based on interviews with students on their experiences with laboratory courses they were following. Previous reviews of laboratory learning have focused on teachers' goals for laboratory courses (e.g., Hofstein & Lunetta, 2004;

Johnstone & Al-Shuaili, 2001; Kirschner & Meester, 1988) but have not considered actual student learning outcomes. This thesis contributes to the description of student laboratory outcomes as described by students and in the literature.

The thesis aims to contribute to the existing knowledge by exploring the students' experiences of laboratory learning and the characteristics of high-quality laboratory teaching at the university level, specifically in pharmaceutical analytical chemistry. This subject is fundamental to drug discovery, development, and quality control, drawing upon interdisciplinary knowledge.

Research questions of this thesis

The underlying motivation for my PhD project was to understand students' experiences of laboratory learning and the significance of laboratory courses for their learning. My project, together with the IQ-lab project of which this is a part, aimed to explore how we can enhance laboratory learning at the university level. I focused on examining the students' experiences of the laboratory as a learning environment. The following three research questions have guided my work:

1) What do university students in chemical sciences learn from laboratory courses, and how do we describe and characterise the learning outcomes?
2) Which factors influence the pharmacy students' experience of laboratory learning?
3) How do second-year pharmacy students experience the role of the laboratory work in the theory-practice relation?

I do not claim that my answers to these research questions are exhaustive or definitive. Given the diverse descriptions of laboratory outcomes presented in paper 1 and the many factors at play in the learning environment (Hounsell and Hounsell, 2007), my findings will obviously not cover every aspect. The laboratory teaching and learning field is complex, and it would be naive to believe that a single answer could encapsulate all its intricacies. Nonetheless, my research has provided valuable insights into the complexity of laboratory education and laboratory learning and contributes to the broader understanding of the subject.

The IQ-Lab project

This PhD project is part of a larger research project on laboratory teaching and learning called "**I**mproving **Q**uality of **Lab**oratory Learning at University Level" (or IQ-Lab for short) (please see www.lablearning.ku.dk)

The IQ-lab is a collaboration between the Department of Science Education and the Department of Pharmacy at the University of Copenhagen. The 3½-year project started in April 2019 but has now been extended to July 2024. The project group has included researchers from both departments. It has involved PhD student Jonas Tarp Jørgensen, Research Assistant Maja Ingerslev Petersen, Assistant Professor Hendra Agustian, Associate Professor Frederik Voetmann Christiansen, Professor Jan Alexis Nielsen, Professor Bente Gammelgaard, and me. Later, Professor Michael Seery and Rie Hjørnegaard Malm were affiliated with the project.

With a focus on laboratory learning at the pharmacy program at the University of Copenhagen (UCPH) the IQ-lab project aims at providing teachers and curriculum designers with in-depth knowledge about which competences students acquire from laboratory work, how they best acquire these competences and how these competences are developed and used after the laboratory courses. In pursuit of this objective, the project aims to answer three research questions:

RQ 1. How can laboratory-related competences in a university pharmaceutical education context be described and characterised?
RQ 2. Which factors influence pharmaceutical students' acquisition of laboratory-related competences, and how can such competences be assessed?
RQ 3. In which contexts and how are acquired laboratory-related competences activated and developed further at later stages in the pharmaceutical program?

In other words, the IQ-lab research project aims to characterize high-quality learning at the university level in pharmacy laboratory education and understand what defines high-quality learning in the laboratory, how it is attained, and how it is brought to use by the students in their further studies. Proper assessment of laboratory related competences concerning formative and summative assessment is also a focus point. The IQ-Lab project consists of six work packages, as de described in Figure 1:

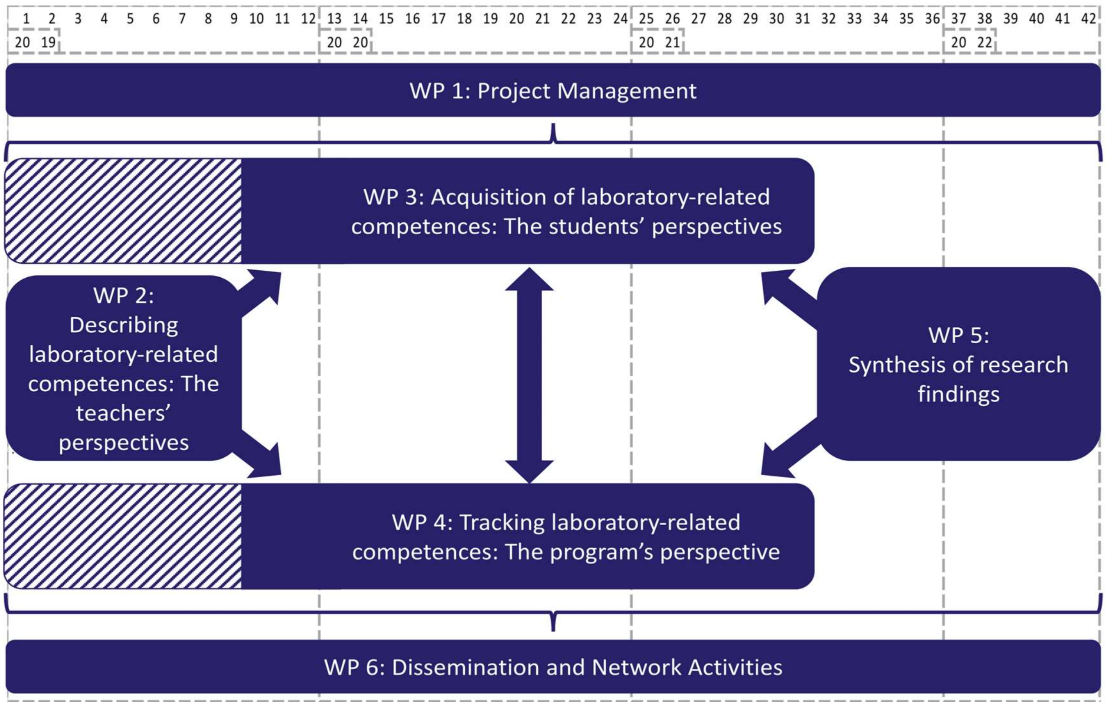

Figure 1: Schematic overview of the different workpackages (WP) of the IQ-lab project. The WP1 and WP6 are not important for the scientific work described in this thesis.

WP3 and WP4 were designed as PhD projects focusing on answering RQ2 concerning the student's perspective and RQ3 concerning the program's perspective, described as the longitudinal development of laboratory learning outcomes. My work contributes to WP2 and WP3.

WP2 focuses on RQ1 by describing the laboratory-related competences from the teacher's perspective. To answer this question, the entire research group collaborated closely on a systematic literature review focusing on empirical evidence of student outcomes resulting from university-level laboratory learning. To contextualise the findings from the review, teachers at the pharmacy department participated in focus group interviews to share their views on their courses' contribution to the learning outcomes found in the literature.

WP3 focuses on the students' perspectives of laboratory learning and RQ2. The project was originally designed as a longitudinal phenomenographic study to examine the qualitatively different approaches and experiences of laboratory teaching and learning among students. The phenomenographic approach was chosen to map these variations effectively. To gather empirical data for the project, interviews with students were planned to obtain detailed descriptions of their laboratory experiences. The project aimed to investigate changes in students' approaches and perceptions of laboratory learning throughout a course by conducting interviews at the beginning and end of the course. The specific disciplinary context for this project was the course Pharmaceutical Analytical Chemistry, which pharmacy students take in the 4th semester of their bachelor's program.

The part of RQ2 focusing on the assessment of laboratory competences was planned to be performed by a senior research member of the group, and this work is presently ongoing. It is led by Assistant Professor Hendra Agustian.

Contributing to RQ3, Jonas Tarp Jørgensen investigated the longitudinal development of laboratory competence by following students throughout their last year at the bachelor's program. Jonas Tarp Jørgensen's PhD project focused on the curriculum. It involved both teachers' and students' perspectives on the progression of laboratory competence over time in the program's third year. The project also sought to delineate the place and role of laboratory-related competences in a program-wide context of pharmacy education. A conclusion from his work is that the nature and execution of feedback on laboratory reports are essential factors in the longitudinal development of students' laboratory learning outcomes. The feedback can determine whether the students succeed in transferring previous learning to future outcomes. Furthermore, it is important that curriculum designers deliberately plan for progression in a program.

Eventually, the findings from the project will be synthesised and generalised into suggestions for improving the practice of teaching laboratory-related competences at the university. This part of the project is still ongoing.

The story of my thesis

Plans often fail to withstand the twists and turns of reality, leaving us to adapt on the fly. This was indeed true about my experience with research and writing this PhD. Here I will describe how the project was planned and how the twists, turns and a pandemic shaped the outcome presented here in this thesis.

In the IQ-lab project we all worked together on the systematic literature review and this endeavour became more elaborate than anticipated. At the beginning of my PhD life, I spent much time manually sorting entries for the review and discussing inclusion criteria. Alongside the work with the systematic literature review, I had to familiarise myself with a completely different qualitative research tradition, having come from a chemistry background and having minimal experience with qualitative methods. The transition from working with chemistry to educational and qualitative research involves a significant shift in methodology. Unlike in chemistry, where physical evidence such as molecules can be measured and identified to eliminate doubt, the theories and models used in educational research and qualitative research are geared towards understanding humans and their individual experiences. As a researcher in these fields, personal involvement may lead to different interpretations of the same data. This is not the same in chemistry; discrepancies most often suggest errors on the researcher's part.

The focus of my PhD project was students' experiences and approaches to laboratory learning and the plan was to conduct a longitudinal phenomenographical study with interviews as the empirical data. Interviewing people is a craft. You get better with practice (Kvale, 2007, p. 48). Since I had no experience with this research method and interviews were intended to be my primary data collection method, I conducted a pilot study early in the project to gain confidence and experience in the interview process. With the help of Maja Ingerslev, a researcher with a background in social sciences and experienced in qualitative methods, we developed an interview guide informed in part by the congruence model (Hounsell & Hounsell, 2007). Structuring my research guide based on a theoretical framework helped me focus on potentially relevant aspects of students' laboratory experiences. Upon analysing the interviews, the students' experience of time played a significant role in their laboratory experiences. This finding was not given from the framework that had informed my interview guide. I conducted a deeper analysis of this finding, which is presented in Paper 2.

After the pilot study, I had acquired some experiences to draw upon for the next interviews. The longitudinal aspects of my research project were planned to come from one round of interviews at the beginning of the course and a second at the end of the course. The interview guides for the two rounds of interviews had different foci based on the hypothesis that students would have a different focus depending on whether they were at the beginning of a course or the end. However, the focus of both interview guides centreed on students' experiences of laboratory teaching and had open questions, which left room for the students to elaborate on what they conceived to be the important aspects of their current learning experiences.

Shortly after the first round of interviews for the longitudinal study was conducted, COVID-19 spread to Europe and closed all the universities in Denmark and the rest of the world. With the closing of the universities, laboratory teaching was canceled, and there was immense insecurity about how long this lockdown would last – none of us imagined at that time the impact the pandemic would have on laboratory teaching the following year (in Denmark and even longer in other parts of the world). One thing seemed certain – the longitudinal aspect of the study I had planned could not be upheld in the designed form anymore. Sitting at home alone, having to rethink my project, I managed, together with my supervisors, to turn this unpleasant situation into an opportunity. The focus of my project was still on students' experiences of laboratory learning. However, I now had a unique opportunity to get insight into students' reflections on laboratory learning *in the absence of it*. I contacted the students I had already interviewed and asked if I could interview them about their experiences of *not* being in the laboratory. Thus, Paper 3 presents the students' experiences of the importance of laboratory teaching in its absence, a perspective that certainly was not part of the original IQ-lab project description. I intended to approach this data phenomenographically in the same way that was the idea in the originally planned longitudinal study. However, as it turned out, the students' experiences were remarkably similar. Phenomenography focuses on the differences in the students' experiences, and I considered the lack of differences in their experiences, the likeness of the students' experiences, a more relevant story to tell. Therefore, I turned to thematic analysis as a qualitative method, a powerful tool to describe similarities in experiences and a more appropriate method for this data pool.

Although I still conducted interviews with students at the end of the course, their experiences were influenced by the lockdown and lack of laboratory work in the course. As a result, I could not determine if students changed their views or approaches to laboratory learning during this laboratory course. However, students have different conceptions of using laboratory experiences to connect the theory in lectures to practical work. In Paper 4, I describe the findings of this analysis and present the different conceptions students hold of how laboratory work supports the theory-practice relationship.

General methodological considerations

Here, I will discuss some key methodological considerations concerning the interview situation and participant recruitment. Subsequent chapters will address methodological considerations specific to the individual papers.

Interviews

Interviews are a common data source in qualitative research, but there are some caveats to consider. The data collection is limited to the students' ability to express themselves. Many students mentioned that it was difficult to describe what they learned in the laboratory; this does not necessarily mean no learning occurred. Students also tend to forget what they did during the laboratory work. In some studies, video clips are used to stimulate the interview by asking about specific situations with the student (see, for example, DeKorver & Towns, 2015; Galloway & Bretz, 2016). There is always some uncertainty with the analyses of what people say because social positioning is at play in every situation. People may try to appear in a certain way, please the interviewer, or the interviewer misunderstand them.

Positionality

Before engaging in the interviews, I considered my positionality regarding the students. Doing interviews can be delicate, especially if the participant talks about sensitive aspects of their life. However, I did not consider the student's experience in the laboratory as especially sensitive, and my experience with the students' interviews was that while the students were undoubtedly emotionally involved, this involvement was not sensitive. Still, as an interviewer, you are in a special position regarding the participants.

In the interview session and the relationship with the participant, the interviewer can be an insider or outsider. An insider is someone from the same group with the same experiences. An outsider is not related to the experiences under investigation (Dwyer & Buckle, 2009). Regarding the pharmacy students I interviewed, I was, on the one hand, an insider because of my background in chemistry and knowledge about laboratory work. On the other hand, I was an outsider because I was no longer a student, and chemistry differs from pharmacy. My knowledge of chemistry can be an advantage because I can understand the terminology used in the lab, and it can help me ask essential questions. A disadvantage could be that I may be prone to relate students' answers to my own experiences and miss details by not asking further questions (Adriansen & Madsen, 2014). To further complicate my position, I taught some students in their first-year Pharmaceutical Physical Chemistry course. Thus, there was a risk that the students considered me a teacher rather than an interviewer. I did not notice signs that the students felt uncomfortable with the situation, and the students had been made aware that I had no formal role in the course (e.g., in assessment tasks, etc.). In this sense, it was beneficial:

I knew them, and they knew me. In some interviews, however, I noticed that the students mentioned me or used my teaching as points of reference to argue their points: 'You are...' or 'I liked that you did...'.

In some cases, they maintained a perspective of me as a teacher ('Please tell [the course responsible] that...'). Thus, some students regarded me as a part of the course team, and they saw me as a contact to the course management. My connection to the course responsible was also established since I participated in some lectures to present my research, and the course responsible for Pharmaceutical Analytical Chemistry is my supervisor.

In my interviews, I experienced that I sometimes got too familiar with the situation and assumed that the student's experiences were similar to mine. In some cases, I assumed their experiences were like other students' I had interviewed. Such assumptions are the danger of being an insider and forgetting to bracket your assumptions and biases towards the research object: I sometimes forgot to ask the students to elaborate on their answers because I thought I knew what they meant. I discovered this situation when I listened to the recorded interviews. Listening to the interviews made me discover the pitfalls during an interview, reflect upon my role as an interviewer, and improve before the next. Sometimes, my attention was not drawn to this before reading the transcripts. At other times, I experienced that my thorough understanding of the laboratory and content helped me to ask questions that gave me access to descriptions of essential experiences. My experiences underline the importance of the researcher's role as a reflective practitioner when doing qualitative research.

Recruiting participants for interviews

During my project, I recruited students for interviews three times: for the pilot study in august 2019 (used in Paper 2), the main project in spring 2020 (used in Papers 3-4), and some additional studies in spring 2021. The recruitment strategy changed each time. For the first study in August 2019, I needed some students willing to participate quite fast. I tried to contact them by message through the learning management system (LMS) and via a post on a Facebook page for all pharmacy students, but I did not receive any responses. I sent a reminder as well, and still no answers. Then my supervisor (teacher at the course in analytical chemistry) approached the students during the laboratory classes after the course I explored. Approached directly and assured that all opinions were valuable, some students volunteered. One student said: "I don't think it is me you want to talk to because I don't like being in the laboratory," – but of course, we also wanted to talk to these students. From a list of names, I contacted the students during a lab course and asked them to join. Only a few students changed their minds when approached afterward. The first round of interviews differed slightly from the rest since the students had finished the course they were interviewed about. For the rest of the interviews, the students participated in the course at the time of the interview.

For the second study, I introduced the project at a lecture for the entire cohort of students in pharmaceutical analytical chemistry (92 out of 200 students present). All students received a short questionnaire, and at the bottom of the questionnaire, there was a box to tick if I could contact them for an interview. From this, 20 students volunteered. Out of the 20 students, 16 responded when approached by either email or a text meassage for those who had provided me with their phone number.

For the last data collection, I decided not to rely on students actively volunteering. This data collection consisted of observations of laboratory group work and an individual interview. I chose to follow one laboratory group in each class (there are typically 12 groups in each of the eight classes). All students were informed of my project, the data collection, and the groups I wanted to follow. When I approached the student groups by message in the LMS, most responded positively to my approach. The few students that did not respond willingly accepted when I approached them in the laboratory. An overview of the interviews is given in Table 1

Table 1: Overview of the time, number, and use of the interviews I have conducted for the work in this thesis.

Time of interview	No of student interviews	Used in analysis
Pilot – august 2019	6	Paper 2
February 2020	16	Paper 4
March 2020	12	Paper 3
June 2020	14	Paper 4
Spring 2021	17	N/A

My experience with recruiting students is that even though it is more pleasant (for you as a researcher) and the most ethical way of recruiting participants is to ask students to volunteer, the best data is gained from actively approaching some students who are not prone to volunteer. I found that the diversity in the students' experiences was larger in the pilot interviews, with only six participants, than in the preliminary study, where I had 16 participants.

Structure of the thesis

In this chapter, I have described the background for the project and how it relates to the larger research project IQ-lab that the project is part of. Further, I explain how this project developed from proposal to actual project and how I managed obstacles such as the pandemic and subsequent lockdowns in 2020 and 2021. Finally, I present some general methodological considerations for doing interviews.

Chapter 2 is related to Paper 1 and describes the working process of writing the review. The chapter seeks to answer the first research question. It includes an overview of previous reviews of major importance and their relation to the research question of the thesis.

In Chapter 3, I describe the pharmaceutical context in which the students I have interviewed work. This chapter seeks to answer the second research question. It includes literature descriptions of which factors influence students' experiences in the laboratory, and I present my findings primarily based on results from Papers 2 and 3. Further, it includes methodological and theoretical considerations regarding Paper 3. The phenomenographical approach used in Paper 2 is described in Chapter 4.

Chapter 4 is closely related to Paper 4 and answers the research question: How do second-year pharmacy students experience the role of laboratory work in the theory-practice relation? In this chapter, I elaborate on phenomenography as a method and research approach used in Papers 2 and 4. I discuss how my choices in the method affect the results I have presented.

Finally, I bring forth some concluding remarks on the work presented here in this thesis and present a model for the learning outcome of laboratory experiences.

The chapters frame and elaborate on the papers' discussion and answer the research questions.

I recommend reading the attached papers before reading the following chapters.

2 – Characterising university students' laboratory learning outcomes – Paper 1

This chapter describes the process of the research group in writing the systematic review and highlights findings from the review that elucidate the students' perspective. Thus, findings relating specifically to students' experience of laboratory learning are discussed in more detail.

Paper 1 describes the students' learning outcomes from laboratory work as manifold and diverse, and we categorise them into five clusters: experimental competences, disciplinary learning, higher-order thinking skills, transversal competences, and affective outcomes. An overview is given in Figure 2.

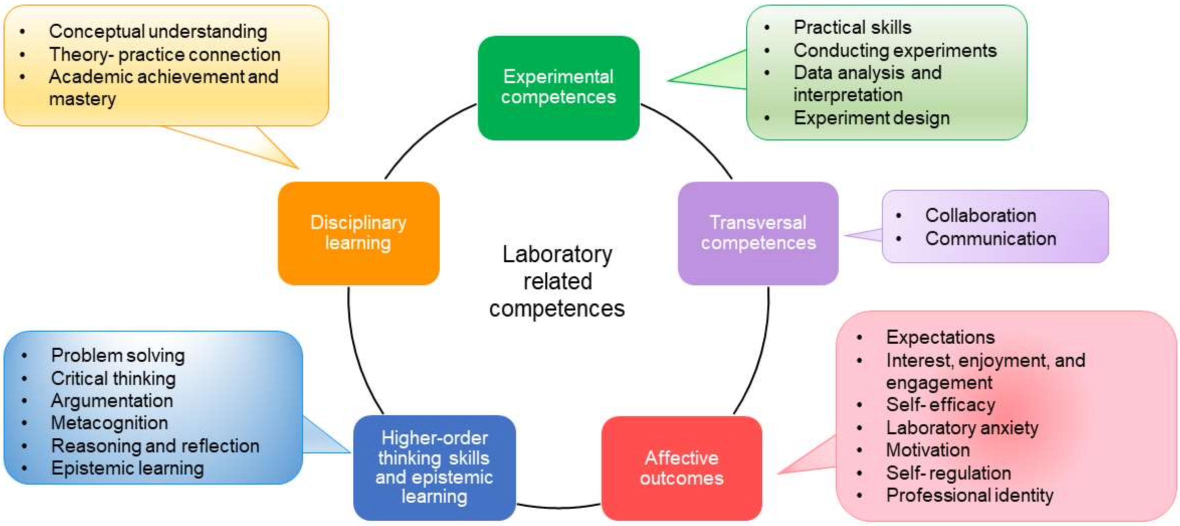

Figure 2: The five clusters of laboratory related competences. Together they encapsule student learning outcomes in the laboratory. Each cluster is described in more details by a related box of concepts entailed in the cluster.

The cluster of *Experimental competences* focuses on students' ability to plan, design, and carry out experiments. It encompasses the procedural processes of conducting experiments, including understanding the purpose of the investigation, performing relevant manipulative skills, analysing, and interpreting data, and evaluating the quality of empirical data. The cluster of *Disciplinary learning* pertains to theoretical or curricular knowledge, understanding the theory-practice connection, and improvements in assessment related to content knowledge. The cluster of *Higher order thinking skills and epistemic learning* involves skills such as; problem-solving, critical thinking, argumentation, metacognition, reasoning, reflection, and understanding of how scientific knowledge is established. Epistemic learning is concerned with learning how scientific knowledge is established, the values and beliefs inherent in the discipline, and the nature, origin, limits, and justification of knowledge. The cluster of *Transversal competences* encompasses general skills necessary for learners. Collaboration and communication skills are highlighted as crucial constructs. The last cluster is that of *Affective outcomes*. This cluster focuses on psychological constructs. It is constructs such as self-efficacy, motivation, and anxiety which have been shown to play significant roles in students' laboratory learning experiences. However, the measurement of some of these constructs can be difficult.

The clusters of laboratory outcomes found in Paper 1 are contextualised in a pharmaceutical context in Paper 5. Through group interviews and workshops with university faculty members from the Department of Pharmacy and the Department of Drug Design and Pharmacology who teaches the courses at the program in pharmacy at the University of Copenhagen, we discussed the five clusters of students learning outcomes from Paper 1. The teachers recognised the importance of laboratory learning and believed it offered unique possibilities for students. The analysis demonstrated that teachers could relate to the constructs and found them observable in their laboratory teaching practices. Basic experimental competences and disciplinary learning were observed in the early stage of the students' education, progressing toward higher-order thinking skills in the bachelor and master's projects.

With this review, we focused on learning outcomes rather than the intended outcomes of instruction. We concentrated on studies that examined what students had learned. Other reviews have focused on the intended learning outcomes represented by teachers' goals for laboratory work (e.g., Kirschner & Meester, 1988; Reid & Shah, 2007). In our study, we have limited ourselves to the tertiary level, unlike much previous research, which also or mainly focused on laboratory learning at primary or secondary levels (e.g., Hofstein & Lunetta, 1982, 2004). With research showing that there are often differences between teachers' goals for laboratory work and students' perceptions of their learning in the laboratory (Richardson, 2005; Virtanen & Lindblom-Ylänne, 2010), there was a need for a thorough and systematic literature review focusing on students' outcomes from laboratory work in higher education because a teacher perspective might not be sufficient.

Descriptions of laboratory goals vs. student outcomes

In this section, I provide a brief overview of previous reviews and compare them to the five clusters of students' outcomes presented here and in Paper 1. PhD Jonas Tarp Jørgensen, responsible for WP3 in the IQ-lab project, provided a thorough chronological overview of the same reviews focusing on his research questions (Jørgensen, 2023).

Common to the previous reviews about laboratory teaching and learning is that they tend to focus on stated aims, goals, or objectives of laboratory learning. They do not focus on students' learning outcomes. Thus, our review distinguishes itself from the rest of the many reviews on laboratory learning by focusing on learning outcomes. In the previous reviews, the authors use many different terms to describe the goals of laboratory instruction: aim, goals, and objectives of learning. I do not see any indication that the authors use the terms differently, so here I will use goals to represent all the terms used to describe the desired learning outcomes from laboratory teaching.

Hofstein and Lunetta (1982) give one of the most prominent reviews of the role of laboratory teaching in science education. The underlying premise of this review was that the laboratory setting possesses unique characteristics in science education, but the effectiveness of laboratory teaching is questionable. The review focuses primarily on secondary-level and introductory science education. Regarding research outcomes, the study does not focus intensely on student's learning outcomes per se. They state that this is due to a lack of quality and comprehensiveness in the research reviewed (Hofstein & Lunetta, 1982). Instead, they focus on identifying *variables* affecting laboratory teaching and learning and suggest that future researchers focus on these. Hofstein and Lunetta (1982) divide the variables into two groups. One group concerns outer parameters, such as instructional methods and the teachers' goals, while the other focuses on student characteristics, such as attitudes, development, and conceptual understanding. Our Paper 1 presents a review focusing on students' outcomes, thus mainly addressing the variables in the second group presented in their study.

Table 2: Overview of learning goals from some reviews of laboratory teaching and learning

Kirschner and Meester (1988)	Lazarowitz and Tamir (1994)	Johnstone and Al-shuali (2001).	Hofstein and Lunetta (2004)	Reid and Shah (2007)
• To formulate hypothesis • To solve problems • To use knowledge and skills in unfamiliar situations • To design simple experiments to test a hypothesis • To use laboratory skills in performing (simple) experiments • To interpret experimental data • To describe the experiment clearly • To remember the central idea of an experiment over a significantly long period.	• Confronting misconceptions • Data manipulation • Logical thinking about science-technology-society • Building values about the nature of science.	• Manipulative skills • Observational skills • Ability to interpret experimental data • Ability to plan experiments • Interest in the subject • Enjoyment in the subject • A feeling of reality of the phenomena	• Understanding of scientific concepts • Interest and motivation • Scientific practical skills and problem-solving abilities • Scientific habits of mind • Understanding of the nature of science • Methods of scientific inquiry and reasoning • Application of scientific knowledge to everyday life	• Skills relating to learning chemistry: e.g., trying out things, seeing theoretical concepts explored in practice. • Practical skills: e.g., handling chemicals and equipment, mastering techniques, etc. • Scientific skills: e.g., observation, deduction, data interpretation • General skills: e.g., teamwork, reporting, presenting, discussing, time management, problem solving

Kirschner and Meester's review (1988) identified 120 different *goals of practical work* at the tertiary level. The authors argue that many of these were either too general or too specific to be useful and informative. They synthesised the essence of these goals into a list of eight general goals for practical work in science. All these goals belong to higher-order thinking skills or the cognitive domain, as we have described the clusters in Paper 1. Thus, Kirschner and Meester (1988) do not focus on the actual student learning outcomes and disregard the affective and social aspects of laboratory learning. An overview of their suggested learning goals is presented in Table 2, together with the results from the following reviews.

Lazarowitz and Tamir (1994) limit themselves only to include four goals for laboratory teaching (table 4). The most significant difference from Kirscher and Meester is that Lazarowitz and Tamir downplay the role of the practical skills, which were highly focused on by Kirschner and Meester (1988) by deliberately formulated goals with active verbs to enclose the practical dimension of laboratory learning. What Lazarowitz and Tamir (1994) bring to the table is a goal aiming to "build values about the nature of science, "thereby stressing epistemic goals for laboratory teaching. This includes the epistemic dimension in the cluster of higher-order thinking skills and epistemic understanding described in Paper 1.

The first review that introduces a focus on goals for affective learning is written by Johnstone and Al-Shuali (2001). Their review was centreed on the purpose, strategies, and assessment methods of laboratory work in chemistry, thereby highlighting the concept of constructive alignment (Biggs, 1996). Notably, they place manipulative skills and affective goals such as interest and enjoyment as individual goals. It is interesting that, alongside discussing constructive alignment, which focuses on aligning learning outcomes, teaching methods, and assessment, they also emphasized affective goals, even though these are typically challenging to assess. Indeed, we find in our review that affective outcomes constitute an essential part of laboratory experiences, and the field of affective outcomes in laboratory instruction could benefit from more research.

Hofstein and Lunetta followed up on their original review (1982) with a second review in 2004 (Hofstein & Lunetta, 2004). One of the main points of this review is that the general view on students has changed in the period, which has been reflected in the research. In 2004, and continuing to this day, the perspective on learning has become significantly more constructivist compared to 1982. As a result, research has increased emphasis on students' experiences, prior knowledge, and personal backgrounds. Their list of goals for laboratory teaching and learning has the same broadness as our findings though lacking the social and transversal components of laboratory teaching and learning.

The last review I include in this section is Reid and Shah (2007), who summarise the role of laboratory teaching in chemistry at the university level in four general goals . Their list is general and generic, and substituting "chemistry" with "pharmacy" or "physics" in the first bullet may make it valid for laboratory work in general. Like the findings from Kirschner and Meester's (1988), Ried and Shar agree that goals for laboratory work need to be clear and that students' perceptions and experiences often do not match the intended purposes – this could be because of the broadness and generality of the goals.

Intended, enacted, and lived object of learning

In educational research, the concepts of the intended, enacted, and lived object of learning are used to describe various aspects of the learning process (Marton, 2014, p. 27). These terms highlight different perspectives and dimensions of how learning takes place.

The intended object of learning refers to the goals, objectives, and outcomes that educators or curriculum designers aim for in the learning process. It represents the planned content, skills, or knowledge that educators intend to teach or for learners to acquire. Educational institutions, standards, or curriculum guidelines typically define the intended object of learning. It provides a framework for instructional design and guides the selection of learning activities and assessments.

The enacted object of learning refers to the actual implementation and realization of the intended learning object in the educational context. It reflects how the learning objectives are translated into practice and how the curriculum is delivered. The enacted object of learning considers several factors, including instructional methods, teaching strategies, classroom interactions, and the learning environment. It recognizes that there may be variations or deviations between the intended object of learning and what occurs in the teaching and learning process

The lived object of learning refers to the subjective and individual experience of the learner. It encompasses the personal understanding, interpretation, and meaning that an individual attributes to the learning process. It focuses on the learner's perspective, thoughts, emotions, and reflections as they engage with the learning materials or activities. The lived object of learning recognises that learners may have unique experiences and interpretations of the intended learning object (Marton, 2014, p. 27).

Our review aims to redirect the emphasis from intended learning goals to actual learning outcomes experienced by students, the lived object of learning. This is a shift towards a more constructivist learning perspective, which is also evident in the second review by Hofstein and Lunetta (2004). Previous reviews and research have primarily focused on teachers' or researchers' goals for laboratory learning, and all descriptions of the learning outcomes in laboratory teaching have been based on these intended learning objectives for laboratory courses. Therefore, our approach in Paper 1 is distinctive as we prioritise students' actual outcomes over teachers' goals.Findings

From our full-text analysis of the 355 articles that fulfilled our inclusion criteria, five clusters emerged describing the students' learning outcomes of laboratory-related competences. These are presented in Figure 2. The clusters are experimental competences, disciplinary learning, higher-order thinking and epistemic learning, transversal competences, and affective outcomes.

The cluster *experimental competence* covers students' ability to plan, design and carry out experiments. Two significant findings from this cluster indicate that student outcomes of laboratory learning can benefit from engaging in authentic laboratory experiences and working with real-world data. An example is a finding from a longitudinal study by Harsh et al. (2011), who developed a mixed methods survey instrument to investigate Undergraduate Research Experiences (UREs), revealing that 46% of respondents considered exposure to genuine scientific research the most important gain from these experiences. These authentic experiences are essential for students' development of epistemic knowledge (Seung et al., 2016) and relate to our findings from Paper 5, where the teachers, based on the five clusters, propose a new structure of the five clusters. They suggest dividing the experimental competence into two clusters, one containing basic practical competence, which should be placed in the middle of the figure as the foundation of laboratory learning outcomes, and a second cluster containing experimental design and more advanced experimental competences.

While students can learn manipulative skills in the laboratory, they may not grasp the broader context of why they are performing specific actions. A finding in the cluster of *disciplinary constructs* is that conceptual discussions should be a part of the practical laboratory work to encourage reflection and refinement of students' conceptions (Galloway & Bretz, 2016; Saribas et al., 2013). Without explicit conceptual discussion activities, students may develop psychomotor skills but not cognitive skills in the laboratory, which is also one of my core findings in Paper 3. In the study by Galloway and Bretz (2016), they observed and interviewed 13 students and found that students often hold off on conceptual reflections until they write their reports after the laboratory practical has ended. Often their first time reflecting on the conceptual aspects of laboratory activities was during the research interviews (that were performed shortly after the laboratory session). By engaging in discussions with teachers, students are supported in their learning and encouraged to consider conceptual aspects of laboratory activities already while performing the practical work in the laboratory, which is also one of the main differences between the two categories of lab experiences in the lab presented in Paper 2. Students in the category of "time for reflection" manages to reflect and discuss the conceptual aspects of the laboratory exercises while doing the experiment in the laboratory, whereas the students that experience the laboratory as a "waste of time" would prefer more classroom teaching because this is where they experience to discuss and reflect upon the conceptual aspects. One way to establish a conceptual focus earlier and bring it into the laboratory is by introducing pre-lab activities and time to discuss. Pre-lab activities prepare the students for the practical and help them reflect on their learning while in the laboratory (Agustian & Seery, 2017).

Disciplinary learning has traditionally held a dominant position in laboratory contexts, primarily due to the ease of summative assessment of disciplinary concepts. However, this dominating role is questionable in laboratory teaching, and research shows that substantive knowledge in science is more efficiently obtained in other ways (Abrahams & Millar, 2008). This is not the least because information overload often characterizes laboratories (Reid & Shah, 2007). When teachers design learning activities for students, they fulfill a dual role. Students must partly learn about content, skills, and methods needed for completing exercises and partly acquire general skills and perspectives for application in their future studies and work life. The first part could be to perform a specific separation using a defined instrument. Marton and Tsui, (2004) refer to this aspect of competence as the *direct object of learning*, while the second general part is known as the *indirect object of learning*. Another way to describe this is that competences contain specific and general aspects (Grønbaek & Winsløw, 2003). What I argue here and what research shows is that the laboratory should be a place for indirect learning objectives because direct learning objectives, such as disciplinary learning, are learned more effectively elsewhere. However, the general nature of the indirect object of learning can make formulating clear goals and assessing the competence more difficult in laboratory teaching and learning.

Our review finds that many of the constructs represented in the affective domain are poorly described in terms of theoretical definitions, which makes measuring these constructs difficult. However, some constructs, e.g., self-efficacy, motivation, and anxiety, have validated instruments to provide a measure for these types of constructs (e.g., see Aydin & Uzuntiryaki, 2009; Mataka & Kowalske, 2015; Winkelmann et al., 2015). These constructs rarely stand alone, and a simple measure of, e.g., self-efficacy does not give any knowledge in itself. To be valid, the measure of, e.g., self-efficacy needs comparison. Often a pre- and a post-intervention measure is used. Further, many of these constructs seem to be intertwined or depend on each other. For example, the construct *interest* is not the only affective measure at play during laboratory experiences, as Galloway et al. (2016) found. Therefore, an instrument only addressing interest will lack essential nuances. Expectations for laboratory learning seem to play a significant role in the students' laboratory learning. In a series of papers, the research group led by Bretz investigated students' cognitive and affective expectations and experiences of learning in the chemistry laboratory (Galloway et al., 2016; Galloway & Bretz, 2015c, 2015b, 2015a, 2016). They developed a validated instrument to measure the students' cognitive, and affective expectations called 'Meaningful Learning in the Laboratory Inventory (MLLI). It is an attempt at an integrated perspective on student learning and assessment in the laboratory, whereby the psychomotor part of doing science is not regarded in isolation, detached from the cognitive and affective parts. In their MLLI, the affective dimension of laboratory learning is reflected in statements such as that students expect 'to worry about finishing on time,' 'to be nervous when handling chemicals,' and 'to be excited to do chemistry' (Galloway & Bretz, 2015a). Based on a cluster analysis, they found that the affective expectations students held in the laboratory affected their experience (Galloway & Bretz, 2015c). Further, one of the papers (Galloway et al. 2016) describes how students who reported higher levels of control and responsibility in the laboratory reported more positive affective experiences, such as enjoyment, interest, and engagement. Additionally, the results showed that students who perceived a high level of control and responsibility in the laboratory were likelier to report greater knowledge and skills gains.

In a study focusing on students' expectations mirroring the studies by Galloway and Bretz (2015b), George-Williams et al. (2019) found based on students' answers to MLLI that students started their university careers with positive expectations of their laboratory experiences. Still, these expectations became slightly more negative each year they were enrolled in the program. This contrasts with Galloway and Bretz (2015a), who find that students have high expectations for laboratory courses. Even though they have unmet expectations in a general chemistry course, many students sustain their high expectations for the next and new course in organic chemistry. However, most students experience that their expectation is unmet during the course.

All these studies show the complexity of the learning experiences in the laboratory and show that the affective dimension plays a significant role in the students' experiences and quality of learning. The affective domain is a crucial factor in influencing students' experiences in the laboratory, and in a recent review by Flaherty (2020), affective research in chemistry is described. The current research presented in the review consists primarily of quantitative research; only 5 % of the articles are qualitative. There are valuable insights to gain from quantitative research, but we need more qualitative research to understand the underlying reasons and motivations of the students. As Flaherty writes, the affective domain holds the key

to understanding “the very reason an individual student would seek to learn at all.” (Flaherty, 2020). This area of research would benefit from more qualitative research.
Our review found that many affective constructs are poorly conceptually defined. An example that points towards the complexity of interest is the findings in the Galloway et al 2016 study. Here they interviewed students about their affective experiences in the chemistry laboratory, and the interviews were guided by a list of 18 affective words (e.g., interested, confused, organized etc.). Students were then asked to circle the words describing their experience of laboratory and cross out the words that did not match their feelings. This exercise was meant to trigger conversations about the students’ feelings. Many students circled interest; however, this was always circled alongside other affective measures, and the students may emphasise interest differently. Research in this area would benefit from qualitative research investigating students’ and teachers’ underlying motivations and understandings about interest and other affective measures.

Methodological considerations on Paper 2

The systematic literature review was done in collaboration with all researchers in the group to secure a shared understanding of how to characterise laboratory competences, which type of teaching and learning activities are conducive to their development, and how these competences can be assessed. This was considered of crucial importance to WP3 and WP4. With the review, we aimed to describe all empirically founded learning outcomes from laboratory teaching. At the outset of the study, we wanted to include studies related to primary and secondary education, but given the number of studies involved (>50000) this was found to be unfeasible. Likewise, in the initial search, we included studies about laboratory learning in all Science, Technology, Engineering, and Mathematics (STEM) disciplines. Still, in the working process, it became clear that we had to narrow it down to chemistry laboratories rather than laboratory work in general. The IQ-lab project is mainly concerned with laboratory learning at the tertiary level in chemical and pharmaceutical education, so it was not a big loss from this perspective.
A review is a tremendous job to do. Mainly because we did it systematically and because we did not want to narrow it down to a specific scientific discipline before the latest possible. In this way, we have a data collection where it is possible to make comparative reviews for, e.g., the physics laboratory or biology laboratory. We wanted to make a map of all the reported student learning outcomes from laboratory courses. However, focusing on educational research literature, we also analysed and identified gaps and inconsistencies within laboratory learning outcomes and laboratory research.

Inclusion criteria

This extensive review was a collaborative work among the group members, and we spent many meetings discussing the process, our definitions of laboratory, and the inclusion criteria. Table 3 shows a final list of inclusion criteria. In the following, I present some additional considerations regarding the process of defining the inclusion criteria.

Table 3 List of inclusion criteria in the screening phase for the systematic review.

1.	Including only educational research
2.	Including only studies concerning science, technology, engineering, and/or mathematics education
3.	Including only empirical studies
4.	Including only studies with a focus on student outcomes
5.	Including only studies about chemistry education
6.	Including only studies related to post-secondary education

For *criterion 1 (including educational research only)*, we had vast amounts of articles to code, so we only looked at the title and the journal. This superficial reading of the articles was necessary to considerably decrease the number of articles. Even though we only looked at the journal and the title of the articles, we marked interesting and relevant articles along the way. Some of these articles we found and read in the full-text version. These full-text papers guided our coding and contributed to discussions about the following criteria. During the discussions, we evaluated possible criteria against our research aim.

For *criterion 2 (including only STEM studies)*, we still only considered the title and journal of the articles. Therefore, we used a broad definition of STEM. We included the articles during the coding process if we were in doubt. However, in working with this criterion, I experienced problems with the level of information I could get from the title and journal; therefore, I often had to investigate the abstracts of the papers.

In developing *criteria 3 (including only empirical studies)*, we had interesting discussions about how a study qualifies to be empirical. Further, we were reaching the limit of what we could elucidate from the abstracts. In an abstract, it is difficult to see how extensive the students' evaluations were and how they used them. During the coding process of this criterion, we needed to make several assumptions about the extent of the studies. The interrater reliability score (Fleiss Kappa) was a valuable tool in this process.

We were limited by the level of detail in the abstracts, and criteria 3 and 4 were based on many assumptions. Therefore, we spent quite some time among the coders to align our understanding of the criteria. We discussed all sorts of proxies for students learning. As coders, we experienced that we could assume what the paper covered based on the abstracts – we also held a precautionary approach to cases where we were in doubt. Then we had a second coder look at the doubt cases.

After completing all these steps, we still had around 3000 articles left – an excessive number of articles for full-text analysis. We found ourselves in a dilemma. We had too many articles to go into further detail, so we needed to narrow the search further but retain the general focus on all STEM disciplines – driven by the idea that there are general competences in all science laboratories. We discussed whether the way to limit the number of articles was to define what we understood as laboratory work.

What constitutes a laboratory?

As we discussed *what constitutes a laboratory*, we examined Ian Hacking's article from 1988 (Hacking, 1988), where he generalises all experimental work and suggests eight familiar *elements of an experiment*. As a part of our discussion, we wondered if we could use these experiment elements to be laboratory work criteria. According to Hacking, experimental work is built of eight elements: (1) The first is a question about some subject matter. (2) Behind this question, there are some established or working theories or background knowledge. (3) Further, there is a *material* side to an experiment, a target, apparatus, and a detector together to make an instrument. (4) Behind the instruments lies theories about the material that help us understand how they work and how to perform the experiments. (5) There are data generators (e.g., humans making measurements or a camera taking photos), (6) the actual data (the measurements or the photos), (7) then there is analysis, reduction, and assessment of data. (8) Lastly, there is the interpretation of the processed data.

This understanding of the laboratory work is important in understanding what goes on in the laboratory with students. However, as an inclusion criterion, we would probably not narrow our number of articles that much down, and it would be challenging to assess the articles and determine the type of laboratory from the abstracts of the articles (and even from full texts). Consequently, we did not use the criterion. Even though we did not end up using this criterion in the inclusion process of the systematic literature review, the discussions and Hacking's eight elements of experiments helped us develop a shared understanding of what an experiment in a laboratory is.

Instead, we concluded that we needed to narrow down the discipline, and inclusion *criterion 5* (only *studies on chemistry education*) was completed without coding; we searched for 'chem' in the spreadsheet with the remaining articles. In hindsight, the work would have been much easier if we had included the term 'chem' in the search string from the beginning, as that would have limited the number of articles at the outset. However, our idea was to keep the possibility of comparative studies open, e.g., the physics outcomes of the laboratory compared to chemistry or biology. This is indeed still a possibility. Inclusion by *criterion 6 (only post-secondary education*) was easy to decide from the abstract and sometimes even the title.

Reflections on the future of systematic literature reviews – AI and ML tools

To do a systematic literature review is a huge endeavour and it took much longer for our group than originally anticipated. During our coding process, we came across Abstrackr ((Wallace et al., 2012), a machine learning (ML) system that we applied in the coding for criteria 6 and 4. The program automatically sorts articles based on previous inclusions and exclusions, presenting the most probable relevant articles first. The advantage of the system is that it rearranges the remaining articles continually such that the "most likely relevant" shows up first – you can in principle stop the inclusion if you for a while do not meet articles that you want to include. Determining "when to stop" is still difficult. We discovered the program rather late in the screening process and had not the basis to determine a good stop criterion. I found the interface to be the most valuable feature of the program for our purposes, particularly its ability to display article titles and abstracts in a clear way. Additionally, I appreciated the function that allowed us to input search terms or indicators, which color-coded the title and abstract text in red or green for unwanted or relevant terms, respectively.

Given the swift advancements in AI and ML tools today and the abundance of relevant resources, it is difficult to envision future systematic reviews being conducted in the same manner as ours. While slogging through all 50,000 articles, we were acutely conscious of this fact, yet we lacked the expertise and the tools to utilise AI to our advantage. However, we did try to develop a ML tool that would use our data to assess future published articles for relevance into our review. We saved all the excel files containing the included and excluded articles, which we utilized to create an ML tool capable of replicating our degree of interrater reliability across the various criteria. Our plan was to train models using this data to scour for related articles in the future and incorporate this as a feature on our webpage, to which interested researchers could subscribe. This idea never came to fruition, though.

When we worked with the analysis, we had help to make a topic analysis based on approx. 450 articles. It was PhD student Jonas Dreyøe who was affiliated with the Department of Science education that did the coding in Python. The ML tool "read" the full text versions and sorted them based on their topics. This is called a cluster analysis. The result from this analysis is a topic map in two dimensions (Figure 2). When marking a topic cluster, the most relevant term for this cluster is highlighted to the right. Based on these clusters and the relevant terms we have described the axes. The analysis did not provide labels for the axis, but we spent some time understanding the "map." We recognised that on one axis, we move from articles having a focus on "discipline, content and specific methods and technology" towards a focus on understanding. The other axis goes from a focus on concepts to a focus on experience (Figure 3). I am including this account not because of the actual results provided by the method, but to show that we were actively engaged in assessing available technologies that could assist us in the review, and we were very aware that the future of systematic reviews would rely much more on technological tools such as AI tools.

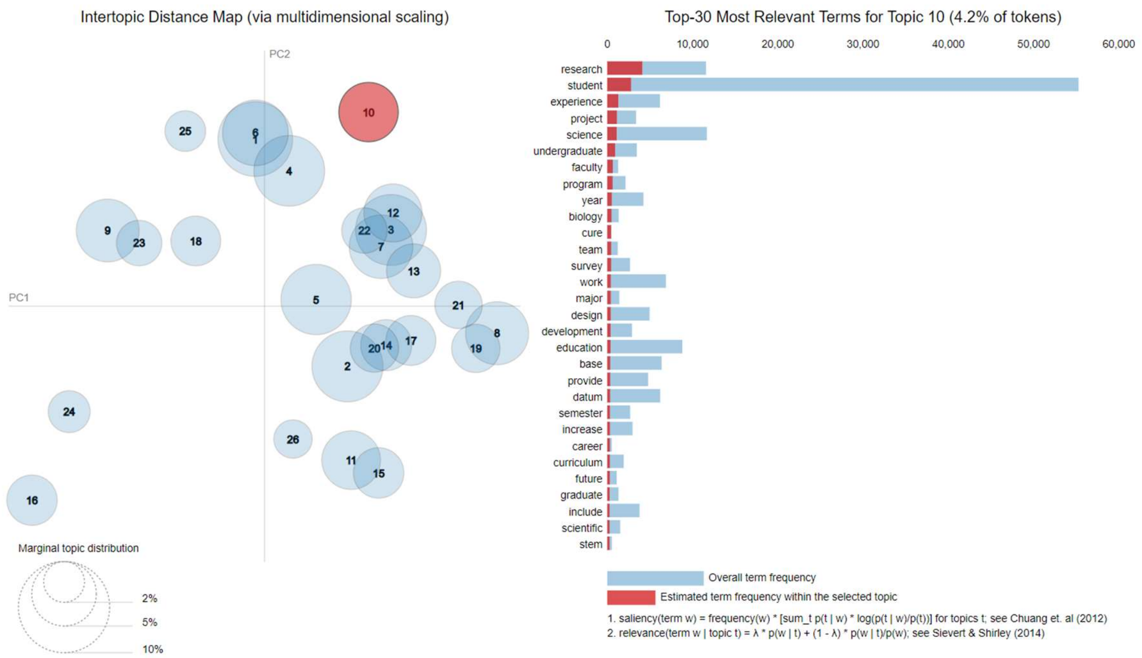

Figure 3 Interactive topic map analysis of 450 full text articles. Each bubble represents a cluster of similar articles. The size represents the marginal topic distribution, meaning that the larger a bubble the more represented the topic in the articles. To the right is a list of the relevant terms for this topic.

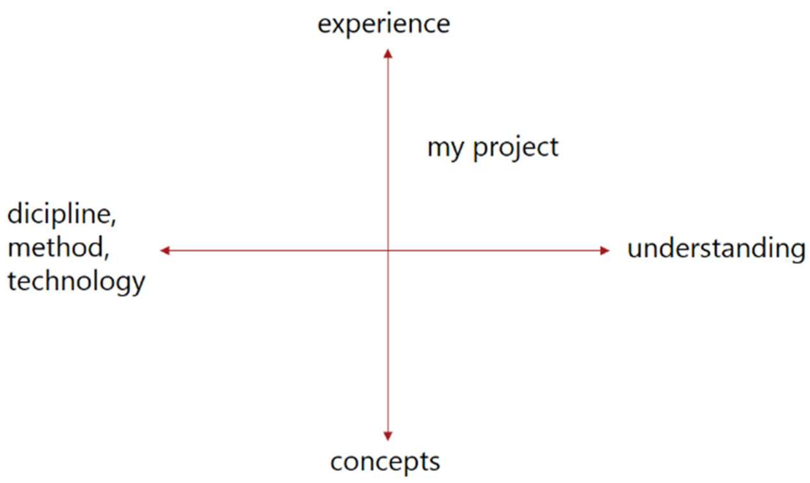

Figure 4 Topic map developed from the cluster analysis of the 450 articles. On one axis, we move from a focus on "discipline, content and specific methods and technology" to a focus on understanding. The other axis goes from a focus on concepts to a focus on experience. My project is in the quadrant of experience and understanding.

In an article by (van de Schoot et al., 2021), they present a new open-source ML tool much like Abstrackr, SRA (Systematic Review Assistant). The authors explain how SRA can automate some of the review processes by assisting with screening, data extraction, and risk of bias assessment. The SRA tool and Abstrackr are used in the screening process, but the development of AI tools is currently very rapid, and soon it will be able to process full-text articles. Provided with appropriate prompts and specifications from researchers, I suggest that the future of review writing will change. Our review is relatively recent, and we spent much time manually including articles. I suppose that much time will be saved in the future by relying on ML and AI tools.

Conclusion

I have described student outcomes in five clusters, experimental competences, disciplinary learning, higher-order thinking and epistemic learning, transversal competences, and affective outcomes. Authentic experiences, working with real-world data, and conceptual discussions benefit students' learning outcomes of laboratory experiences. The affective domain plays a significant role in students' experiences and learning outcomes of laboratory experiences. More qualitative research is needed to understand the underlying motivations for learning in the laboratory. Furthermore, I discussed the process of conducting a systematic literature review and outlined our efforts to utilise AI and ML tools to enhance and streamline the process. Undoubtedly, AI tools will increasingly play a significant role in future systematic literature reviews, offering improvements and facilitating the overall process.

3 – Factors influencing students’ experiences of laboratory learning – Papers 2 and 3

In this chapter, I will seek to answer the second research question: “Which factors influence the pharmacy students' experience of laboratory learning?” The answer in this thesis combines the findings in Papers 2 and 3. I will start by providing some context about the pharmacy program the students I have been interviewing are following. I will then introduce some key research findings from the literature about factors influencing pharmacy students’ experiences in the laboratory. Then I will present central findings from my two papers, Paper 2 and 3, that I believe contribute to answering this question.

In the last part of the chapter, I will provide methodological perspectives on thematic analysis, which was the primary method of analysis in Paper 3. The methodological considerations concerning Paper 2 will be provided in Chapter 4, as this study used a phenomenographical method more in line with Paper 4.

Context of study

The Danish pharmacy program

The pharmacy program at the University of Copenhagen (UCPH) follows the 3+2 Bologna structure, with three years for the Bachelor of Pharmacy degree and additional two years for the Master of Pharmacy (or Master of Pharmaceutical Sciences, depending on students' choices in the program). The School of Pharmaceutical Sciences at UCPH is responsible for one of two pharmacy educations in Denmark.

Only about 15 % of the graduates in a cohort from UCPH work as pharmacists for community and hospital pharmacies, while the large pharma and life science industry employs many of the graduates (Vestergård, Nørgaard, Kaae, 2017). In the US, 44% and 30% of practicing pharmacists work in community pharmacies and hospitals, respectively (Bellottie et al., 2018).

The pharmacy education is underlaid EU directives (European commission, 2005/36/EC chapter 3 section 8) that describes general guidelines for the Master of Pharmacy. These directives include a 6-months pharmacy internship, which is compulsory for obtaining certification for working in a pharmacy. Students who opt out and do not follow the internship can instead choose the Master of Pharmaceutical Sciences with the opportunity to follow more elective or tailormade courses. From a recent graduate survey from the Master of Pharmacy, it is clear that even though the students have the internship and are qualified to work at the pharmacies, only 41% and 40% percent apply for jobs in community pharmacies or hospitals, respectively, while 92% had applied for a job in the medicinal or biotech industry(*Farmaci Dimittendundersøgelse*, 2020).

With most candidates pursuing careers in industry rather than in community or hospital pharmacies, the bachelor program is structured with a heavy focus on natural sciences such as organic, physical, and analytical chemistry, biochemistry, and pharmacology. Besides social pharmacy, pharmaceutics is represented in courses of drug development. The bachelor project is centreed on drug development and control. Figure 5 shows an overview of the courses in the BSc program in Pharmacy. Most of the red, blue, and yellow courses in Figure 5 contain laboratory work.

During my PhD, I visited the University of Utrecht in the Netherlands, and their pharmacy program is much more focused on the use of medicines and less on their science background. In that program (*Pharmacy Bachelor's Program at University of Utrecht*, 2023) many of the courses are directed towards a specific indication, such as “oncology”, “dermatology” or “skin conditions”.” In contrast, the Danish courses focus on the underlying scientific principles through courses as “organ pharmacology” or “cellular and molecular biology”. Thus, the BSc pharmacy program at UCPH is quite different from many international Pharmacy programs and has a stronger natural science/chemistry focus on drugs compared to many other international programs that aim more specifically at pharmacy employment.

Sem 1	Sem 2	Sem 3	Sem 4	Sem 5	Sem 6
Drug development - from molecule to man	Pharmaceutical Physical Chemistry I	Pharmaceutical Physical chemistry II	Pharmaceutics I - Liquid and Semi-Solid Dosage Forms	Pharmaceutics II - Solid Dosage Forms	Bachelor's project
Organic Chemistry I – Physico-chemical properties	Organic Chemistry II - synthesis of drug molecules	Biopharmaceuticals - bioorganic chemistry	Pharmaceutical Analytical Chemistry	Drugs from Nature	
Chemical Principles	Evaluation of Pharmaceutical substances	Philosophy of Science and Social Pharmacy	Social Pharmacy - Methods and Dissemination	Pharmaco-therapy	Elective
Cellular and molecular biology	Pharmaceutical biology	Basic Pharmacology	Organ Pharmachology	Systems Pharmacology - Signalling pathways	Elective

Development and production of drugs
The Chemical basis for drugs and drug substances
The pharmacologic al basis for drugs and drug substances
Use of drugs

Figure 5: An overview of the curriculum for the bachelor's program in pharmacy. This has been the curriculum more or less unchanged since 2015., The colours show 4 different "strands" of courses where green=social sciences, yellow= pharmaceutical, red= biological and blue=chemical.

The course Pharmaceutical analytical chemistry

The students I interviewed for Papers 2-4 were all participants in the course Pharmaceutical Analytical Chemistry. The course is a 7.5 ECTS compulsory course in the program's second year. The course consists mainly of laboratory exercises (16x4 hours) supplemented by lectures (19h). The students conduct eight different exercises for which they prepare a report that the teacher must approve. The course's central learning objectives are to choose appropriate analytical methods for pharmaceutical problems, conduct the experiment using appropriate calibration methods, critically evaluate data and report the results. Figure 2 in Paper 2 gives an overview of the course's laboratory work.

Factors influencing pharmacy students learning according to published literature

Surprisingly, limited research has beenedicated to pharmacy laboratory work, including conducting experiments (Anakin & McDowell, 2021). Consequently, in this context, I will assume that findings applicable to chemistry students in a chemistry laboratory also hold some validity for pharmacy students, particularly given the chemical orientation of the UCPH pharmacy BSc program. Throughout the following discussion, I will explicitly indicate whether the research pertains to pharmacy or chemistry students.

Pharmacist identity

Much attention is given to the importance of identity formation in the literature about pharmacy students' experiences of learning through practical and laboratory work. Pharmacists have a unique role in society, and specific jobs demand a pharmaceutical education. Therefore, the students have a defined professional role to fulfill, and the education program should help shape and prepare them for their future jobs.

In a study by Burrows et al. (2016), they survey final-year students in Australia. The students are in their last year in either a four-year bachelor's or two-year postgraduate master required to become a pharmacist. They find that the students describe their perception of their role as pharmacists as primarily a dispensing and counseling role. Other understandings of the pharmacist's role focused on communicating about medicines, gathering information to review medicines, identifying medication-related problems, and caring for patients' health as part of the health care system. All these perceptions concern pharmacists' role as medical experts in a pharmacy setting. This finding is reflected in a study (Vestergaard et al., 2017) where Danish pharmacy students are followed during their pharmacy internship (in their master's program). The study investigated customers', supervisors', and students' perceptions of the professional role. At the end of the internship, students found that "being a clinical leader" was the most important task for the community pharmacist. This indicates that at the end of the MSc program, the students have well-shaped conceptions of the professional identity and tasks of the community pharmacist and that they see the importance of clinical perspectives – shaped, not least by the internship, which is part of the MSc program.

Table 4: Data from 2022 and 2021 on a question posed as part of a lecture in a course. Students could only select one preference. The overall question was, "Why have you chosen to study Pharmacy." For 2022 n=188, the number of participants in 2021 is unknown, but likely similar.

	2022	**2021**
Tradition - at least one in my family is a pharmacist (farmaceut)	3,20%	6,50%
Think medicines/drugs are interesting	36,20%	36,60%
want to develop drugs that can save lives	27,10%	27,80%
want to work in a pharmacy	0%	1,40%
want to be a pharmaceutical expert	6.9%	5,60%
want a job with a good salary	10.1%	7,40%
the study is a good combination of biology, chemistry, and physics	12,20%	9,70%
for other reasons	4.3%	5,10%

When students enroll in the BSc, the role of community pharmacist is probably less well understood. As part of the introductory course ("Drug development – from molecule to man"), a teacher at a first-year course asked the students why they chose pharmacy education. For the two cohorts I have data, very few students answered that they wanted to be a pharmacist in a community pharmacy. In contrast, most students expressed a more general interest in drugs and drug development. The data are presented in Table 4.

The internship required to become a pharmacist at UCPH is placed in the master's program. Although the students I interviewed do not need to choose whether to follow the internship before the master's level, my interviews show that in the 4th semester of the BSc, they are actively thinking about this job trajectory. So there seems to be a change in the students' perception of what to do with their education throughout their studies, from almost zero percent wanting to be pharmacists in community pharmacies to considering it at my interview in the second year.

In a study of pharmacy students at a Texan university, Diec et al. (2021) investigate fourth-year pharmacy students' experiences of non-technical skills development. What is perceived to be the most essential skill is professionalism. The definition of professionalism is taken from the Accreditation Counsel from Pharmacy Educations (ACPE) standards 2016, in which Standard 4 defines professionalism as: "The graduate is able to exhibit behaviours and values that are consistent with the trust given to the profession by patients, other healthcare providers, and society." (Accreditation Council for Pharmacy Education 2015). This importance of professionalism and identity formation is also found in a study by Taylor and Harding (2007). This study investigates first and third-year undergraduates in four different pharmacy schools in England. They find that initially, students perceive and experience pharmacy education as primarily focused on acquiring a fundamental scientific knowledge base rather than preparing for a professional role in a practical setting. This is not hugely different from the structure at UCPH, where there is a strong focus on the natural sciences at the bachelor/undergraduate level. While there is a valid argument for establishing a solid foundation in scientific principles to guide future practice, it is equally important, and even essential, to introduce elements of professional practice to pharmacy students from the beginning of their training, according to Taylor and Harding (2007).

Authentic experiences

In a review of identity formation in pharmacy, (Noble et al., 2019) states that it is important to integrate identity-forming experiences into the curriculum. Noble et al. (2019) work with the definition of identity as a sense of being a professional that forms through interactions with self and context. The study describes that professional identity development takes place through student engagement with authentic learning activities, curricular alignment with work practices, and interactions with practicing pharmacists, much like what is described in the study mentioned above by Taylor & Harding (2007).

For the bachelor study in pharmacy at UCPH, it is more challenging to incorporate relevant, authentic experiences because students end up in more diverse positions when they finalise their education. Further on, students at the Bachelor of Pharmacy program at UCPH, besides the pharmaceutics courses, are exposed to natural sciences courses. Hence, many learning activities relate to authentic experiences as a scientist with drug expertise.

Authenticity is sought at the program because all courses in the Bachelor of Pharmacy at UCPH are focused on and somehow relate to pharmaceuticals. Thus, the identity forming through the experiences will likely be a pharmaceutical sciences expert identity rather than a pharmacy identity, as the students also described in the study by Taylor and Harding (2007).

Authentic experiences of research are found to be of importance in chemistry students' experiences and the development of laboratory-related experimental competence. An example is the study by Harsh et al. (2011), who reported that students considered 'exposure to genuine, authentic research experience' most important (49%) for their laboratory experience.

Teacher qualifications

In an article by Vahdat (2009), the focus was on reforming the medicinal chemistry course in Australian pharmacy education. This course covered analytical chemistry and drug design techniques. The researchers conducted surveys to gather students' feedback and experiences with the course, leading to the identification of several factors influencing their overall perception. One crucial aspect highlighted by the students was the quality of the laboratory demonstrators, teaching assistants, or teachers (TAs). They expressed dissatisfaction with the TAs' level of understanding and communication skills, perceiving their presence as detrimental to the effectiveness of the laboratory experiments (Vahdat, 2009). The level of the TAs' understanding of the subject matter and their approach to learning and teaching significantly impact students' outcomes and experiences in the course. Similar studies conducted in the field of chemistry emphasize this importance as well (Current & Kowalske, 2016; Wheeler, Maeng, & Whitworth, 2017). Introducing a targeted teaching course for TAs has positively affected students' laboratory practical experience.

In the MSc Pharmacy graduate survey from 2020, graduates were asked to assess the disciplinary and pedagogical competences of the teachers in the program. 84% of the graduates in the study found that the disciplinary competences of their teachers overall were "good", while the remaining 16% were "medium". Regarding the pedagogical competences only 12% were assessed as "good," whereas 63% were "medium" and 23% were "bad" (n=113). From these numbers, it appears that in the UCPH context, the teachers' pedagogical competences, rather than their understanding of the subject matter, might be improved.

Feedback and reflection

In a review of learning styles and learning approaches, Tsingos et al. (2015) highlight the importance of reflection in pharmacy education so that students can bridge the gap between theory and practice (Tsingos et al., 2015). That reflection is the foundation for connecting the experience in the laboratory to the theory of the lectures, which is also argued by Galloway and Bretz (2016) in a study with chemistry students. In the latter study, the authors video recorded the students during a lab session and interviewed them about their experience afterward. During the interviews, the researchers showed the students short video clips of their experiments and asked them to explain what they did. Few students could correctly explain the chemistry and expressed that they were so focused on doing the chemistry that they saved the thinking and reflections to report writing later. So, the first time the students reflected on their experiment was during the interview. This point to the importance of reflection and feedback *during* lab work to bring in meaningfulness and connect the psychomotor and cognitive domain.

Affective experiences

In continuation of the studies described above,Galloway et al. (2016) conducted a study focused on the students' affective experiences in the laboratory. During interviews with the same students described above, they also asked the students to identify the feelings they experienced in the laboratory. It was evident that students had a lot of feelings during laboratory experiments, and how they handled these feelings defined the students' experiences in the laboratory. The feelings both affect their thoughts and their actions. The students' perception of control and responsibility for their learning shaped their learning experiences in the laboratory. When students experienced that the laboratory exercises were straightforward, they overlooked the opportunity to consider the chemistry behind them. This points towards the importance of the *type of instruction* in the laboratory – that it is important to incorporate aspects of the instruction that offer the students some autonomy and gives them responsibility for learning because then the likelihood of them taking it is larger.

Constructive alignment and congruence

In the study conducted by Vahdat (2009), pharmacy students demonstrated an appreciation for integrating course components. Specifically, the students expressed a desire for the lecture materials and laboratory experiments to be closely aligned. These findings are consistent with Borrmann's research (2008) which highlighted the high level of appreciation among chemistry students for connecting theory with laboratory observations. From a more general university pedagogy perspective, course integration is a crucial aspect of constructive alignment (Biggs, 1996). Biggs has described how aligning course goals, teaching activities, and assessment methods could enhance student outcomes. Constructive alignment is a general concept that applies across disciplines, including pharmacy and chemistry. In these fields, alignment between laboratory experiments and lecture theory is essential.

A study by Hagemeier and Mason (2011) surveyed pharmacy students' perception of testing and study strategies related to tests and found that the number of tests and if they were graded or not determined how the students studied for them, highlighting the importance of the assessment method and timing in the students' experience of learning. The study concludes that teachers should use tests that aim to improve learning rather than tests that "simply generate grades." This points to a more general point about how formative and summative assessment plays together, which also needs to be considered (e.g., Harlen & James, 1997).

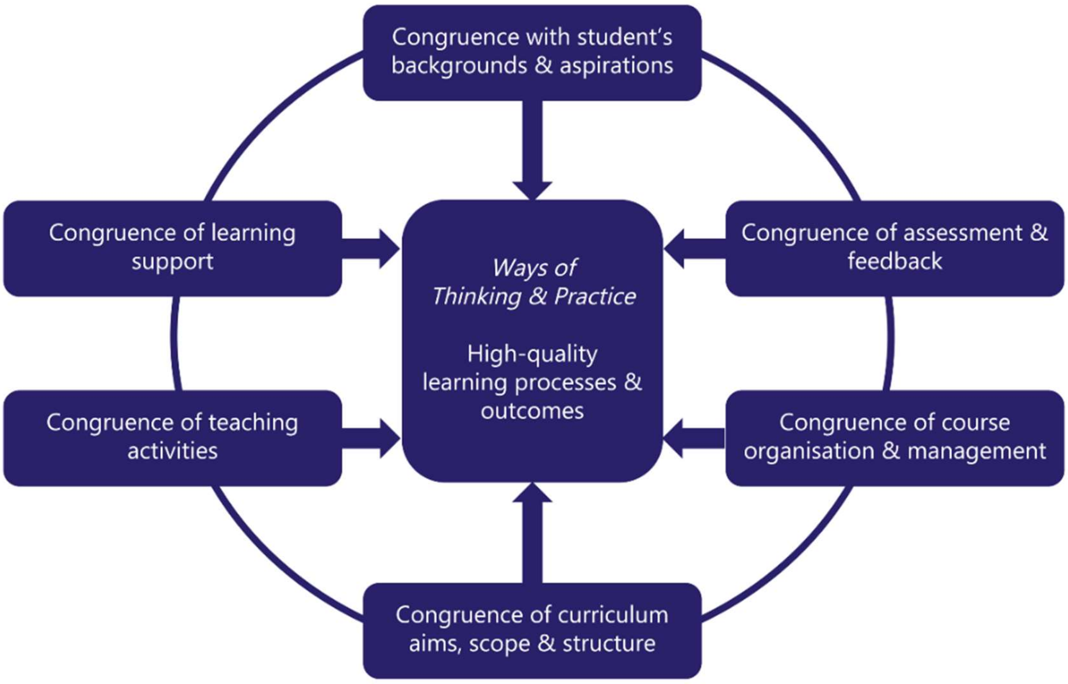

Figure 6: Congruence model of teaching-learning environments (after Hounsell & Hounsell, 2007)

Vahdat's study (2009) also emphasised the significance of effective course management. They highlighted that the role of course management should not be underestimated, as the cohesiveness of a course can unravel without proper management. Congruence is another construct that encompasses both course management and constructive alignment as presented by the ETL project (Enhancing Teaching-Learning Environments in the University, Entwistle, 2014; Hounsell et al., 2005). While constructive alignment focuses solely on the alignment between intended learning outcomes, teaching-learning activities, and assessment (Biggs & Tang, 2011, p. 95), the congruence model incorporates six aspects of the learning environment that needs to be in congruence: students' background and aspirations, feedback and assessment, course management and organization, curriculum aims and goals, teaching-learning activities, and learning support (Figure 8).

The researchers involved in the ETL project highlight that congruence in students' learning experiences is a prerequisite for high-quality learning. They define high-quality learning as the development of discipline-specific "ways of thinking and practicing" (WTP) (Hounsell & Hounsell, 2007). The concept of WTP encompasses values, knowledge, conventions, and epistemic aspects specific to a particular discipline. The ETL project inspired the current project but did not focus specifically on laboratory courses in their empirical data. Despite this, the ETL project reported that laboratory teaching and the practical education component are crucial for developing WTP in the biological sciences (Mccune & Hounsell, 2005).

Students' approaches to learning

Decades ago, starting in the '70s, researchers found that students had two distinct approaches when reading a text (Marton & Säljo, 1976). One way to approach a text was to learn facts and recall specific entities. The other focused on the meaning of the text. These approaches are now widely recognised (Biggs & Tang, 2011, p. 24), and we refer to them as *surface* and *deep approaches to learning*, respectively. Besides the deep and surface approach, there is also a strategic approach to learning.

The deep approach to learning is characterised by wanting to find meaning. Students who adopt this approach activate prior knowledge and earlier experiences and use an active learning process. One way is to take a holistic approach, looking for relations, patterns, and principles; another is to use evidence and examine an argument's logic. When applying a deep approach to learning, students also monitor their development of understanding (Entwistle, 2000). In contrast, students focus on remembering facts and coping with the task when applying a surface approach. They see the information as unrelated bits, so rote memorisation is a method of choice when using this approach to learning. A student that applies a strategic approach is performance-oriented and switches between deep and surface approaches depending on how to best perform in, e.g., an exam (Biggs & Tang, 2011, p. 36).

In the review by Tsingos et al. (2015), they only find few studies of pharmacy students' approaches to learning. A study conducted with Australian undergraduate pharmacy students pursuing a four-year bachelor's degree employed the Inventory of Learning Styles (ILS) to assess the students' learning approaches (Smith 2007). This survey differentiates between a deep, surface, unidirectional, and applied approach to learning. They found that the most prominent approach to learning for pharmacy students was the applied approach. Whereas the least used was the deep approach to learning (Smith et al., 2007). They did not find significant changes over time, and both first- and fourth-year students had the same preferences for learning approaches. The authors compare this result to research in other disciplines, and no consistent patterns arise, suggesting that the learning approaches in higher education are influenced more by the learning environment than the subject matter within the particular discipline.

The studies I have found on pharmacy students' experience in learning are not about laboratory learning. Since the laboratory is a significant learning environment, this is a problem, especially since research points to the importance of considering the context of the learning environment. Few studies in chemistry focus on students' approaches and perceptions of laboratory teaching and learning. A few studies have investigated students' conceptions of laboratory learning in a chemistry context, and research has found conceptions and approaches to learning are closely connected (Richardson, 2005). Conceptions and approaches dictate how students perceive their learning process and subsequently adapt their strategies to align with their beliefs; therefore conceptions are also interesting to investigate. Burrows et al. (2017) conducted a study on a non-traditional project-based organic chemistry course, revealing eight distinct perceptions of the course that led to diverse approaches to learning. Further, Chiu et al. (2016) investigated science students' conceptions of learning science by laboratory. They found six conceptions: memorising, verifying, acquiring manipulative skills, obtaining authentic experience, reviewing prior learning profiles, and achieve in-depth understanding.

Students' conception of learning are both domain and context-specific. This is evident in a study by (Tsai, 2004) where they investigate students with different majors. The students with science majors had generally more advanced conceptions of learning science than those majoring in arts. In addition, it would probably be the other way around if they had investigated conceptions of learning art.

As shown above, many factors play a role in pharmacy and chemistry students' laboratory learning experiences; however little research has focused on laboratory situations and courses in their study. Thus, below I will elaborate on how Papers 2 and 3 add to our understanding of the experience of laboratory learning.

Findings – factors influencing pharmacy students' experiences of laboratory learning

Students' conceptions of time in the laboratory

The students' perception of time in the laboratory is essential for their learning outcome and is closely connected to their approach to learning. Paper 2 describes two qualitatively different experiences of time in the laboratory. Students can experience the time in the laboratory as *time for reflection* or a *waste of time*. These two experiences of laboratory teaching highly affect the students' approach to learning. Students who experience the *time for reflection* tend to apply deep learning approaches, while students who experience the laboratory as *a waste of time* adopt more surface approaches to learning in the laboratory.

When students experience the scheduled time in the laboratory as adequate for the tasks expected to be performed and perceive the lab time as a time for reflection, it is more likely that they will engage in discussions, try new things, and have minds-on while hands-on. However, if they feel pressure from a crowded schedule, they are more likely to divide the work between group members, focus on producing data, do all the steps, and "get through the exercise." This leads to a surface approach where students, e.g., postpone the evaluation of their data and the experiment to post-laboratory activities such as report writing. This makes the students perceive the time in the laboratory as a waste of time because they associate learning with activities *outside of the laboratory*.

There is a relation between the students' experience of time in the laboratory and their experience of congruence between the laboratory activities and the exam. Students in the *Time* *for reflection* category perceive and experience a connection between the experiments, the report, and the exam and actively use the laboratory experience in the exam situation. On the contrary, students who experience time in the laboratory as a *waste of time* do not experience that laboratory activity relates to the exam. They become separate and disparate activities that the written report does not connect.

In Paper 3, I rely on Latour and Woolgar's description (Latour & Woolgar, 1986) of the scientists in a research lab (elaborated further in the methodological considerations below). Their work is characteristic in how they alternate between working in the "work benches" and the "offices." They describe the laboratory as a venue for "text production," where materials and instruments are central in the text production. The students in Paper 2, with the understanding of *Lab as time for reflection,* integrate all parts of the laboratory experience by moving back and forth trough the "office" and "laboratory spaces" in the teaching laboratory, using the time to learn from peers, teachers, and the data. Conversely, the students that experience the laboratory as a *waste of time* tend to separate "office time" and "laboratory time" and experience less coherence.

Table 5: Summary of student conceptions of time and their experience of congruence

Category	Assessment	Teaching-learning activities	Course organisation	Support
Waste of time	Surprised by the exam; no connection to the laboratory.	Practical work takes too much effort. Lose overview and focus on external requirements. Learning happens outside of the laboratory (report or exam reading)	Rigid understanding of what they should do.	Do not feel that they get sufficient support and do not seek it.
Time for Reflection	Actively uses experiences from the lab to the exam—clear connection with lab activities.	Possibility to see a connection between practical work and theory, ask for help, and learn.	Actively uses the waiting time in the lab to proceed with reports.	Learn from discussions with teachers or peers.

In Paper 2, I have identified the students' conception of time as a crucial factor in shaping their laboratory learning experience. As mentioned, the conceptions of time are closely related to the students' approach to learning. It is clear from my findings that the students' experience of time in the laboratory also shows itself in the different areas of the congruence model. One factor is, for example, the specific course design. It determines the actual time available to the students to learn. If students must rush through the exercises, leaving little time for reflection along the way, then that will probably lead more students to conceive of time in the lab as a "waste of time." The same can be said about their approaches to learning. In that sense, both students' conceptions of time and approaches to learning are complex factors conditioned by many aspects of the learning environment.

Assessment

In Paper 2, I describe how students' perception of time relates to their experience of congruence with the exam. In my data, I can often see how the type of questions asked in the exam and the type of exam (oral, written, etc.) shape or influence the students' perceptions of what is important (the so-called backwash effect (Biggs & Tang, 2011, p. 197). Pharmacy students at UCPH are mainly exposed to written exams tending to focus on theoretical concepts and calculations. Some students seem to have a very pragmatic understanding of "theory," as all that must be read or written. Therefore, when the exam is in writing, they think of it as "theory" and detached from the laboratory work. This is also discussed in our review (Paper 1). With the exam, the teachers send a strong message to the students about what is essential in the course because it is worth assessing.

Feedback and scaffolding

In Paper 3, I describe the students' experience of the lack of laboratory teaching (during the Covid lock-down). In the interviews, the students emphasise the importance of close contact with the teacher, a characteristic of laboratory learning. This informal and close contact is essential because it gives the students more helpful feedback and proper scaffolding of their learning. Students describe that the teacher interaction is important for their learning experience. The relations the students build with the teachers through informal contact in the laboratory provide timely feedback on their practices and thinking processes. This feedback supports their learning. In addition, it helps the students shape their ways of thinking and practicing in the laboratory.

The teacher plays a crucial role in the laboratory, not only as a guide for students in fostering meaningful reflections and learning (Galloway and Bretz, 2016) but also as a role model who shapes students' identities and provides emotional support in challenging situations. Teachers must scaffold students' emotions, as their affective experiences in the laboratory and how they respond to them influence their learning outcomes (Galloway et al., 2016). Therefore, teachers should be able to identify and guide students through these emotional experiences to facilitate their learning.

Experience of transformation and embodied structure

The second part of paper 3 describes the students' experience of transformations. The theoretical framework from Latour and Woolgar (1986) about understanding the laboratory as a place for text production provides, despite its age, a fresh perspective on understanding laboratory learning. What I mean by this is that the construction process of laboratory knowledge through transformations is not given (enough) emphasis in current laboratory learning research. It is important for students' epistemic understanding of the role of the laboratory to experience the transformations that happen in the laboratory. Students highly value the experiences of the transformations of materials into literary inscriptions (graphs, text, and the like) that occur in the laboratory. The transformations are important for the students to develop an understanding of scientific argumentation.

These transformations occur within both the teaching laboratory and the research laboratory. Experiencing and comprehending these transformations provide authentic experiences that contribute to developing a pharmacist's identity in an analytical laboratory. Noble (2019) emphasized that authentic laboratory experiences play a vital role in identity development. Therefore, teachers should carefully consider how they could replicate the functions of research laboratories or other laboratory-related activities in their labs. By providing these authentic experiences, students can experiment and cultivate their identity within this field. Teachers understanding the importance of the transformations of knowledge that occurs in laboratory work for student learning can consider it in course planning: Which transformations should students meet in specific exercises/reports, and how can they be supported in making them, e.g., by relevant feedback?

The teaching laboratory provides students with first-hand experience of transformations of knowledge. It offers them an embodied structure to support their learning (whether temporal, narrative, or causal, as described in Paper 3). Thereby the students are given more ways to enhance their understanding.

Identity formation

So far, I have only presented factors based on my data collection's published or submitted material. I have earlier touched upon the identity of a pharmacist, and here I will present some preliminary findings of the students' potential identities.

It is evidently present in the pharmacy students' minds that their education directs them towards specific career opportunities, including working in a pharmacy (as discussed before). The students in my interviews often mention that there are certain jobs for them on *the other side*. The "other side" refers to the labour market and their professional lives after finishing their education. In the interviews, the students have an image of certain realities outside the educational setting. Depending on the students' prospects, this imagined reality on the other side shapes how they perceive laboratory teaching and learning. Thus, the students' future identity and prospective job aspirations may shape their understanding – a quite different kind of "backwash" than the one provided by the exam. Their wish for the future certainly gives them perspectives on laboratory learning.

In Table 6, I present the different jobs the students mention in the interviews, and I describe how the laboratory's role relates to this job according to the students. The table shows that the lived object of learning as presented in chapter 2 depends on the students' perceived identity or how they see themselves in the future. The student who imagines that practical skills will be essential in the future perceive these as important laboratory learning outcomes. In contrast, the students that think of being a pharmacist at a community pharmacy know that they will have a more counseling role in their job and not use their practical skills from the laboratory; they perceive the lived object of learning from the laboratory to be more general to understand some basic concepts of drug discovery, control processes, and manufacturing.

Table 6: Pharmaceutical realities expressed by the students

Job or profession	Quote from student	Role of the laboratory
Pharmacists	”Compared to a regular job at a pharmacy, it [the laboratory] gives an understanding about how things work. Or e.g. the drug, how is it produced. It is more important to know as a pharmacist than as a consumer” (D11-1) ”What you work with as a pharmacist afterwards, it is all produced in a lab and has been through a lot tests, so basically it all originates from the laboratory. So, to get that understanding about how things are handled and produced before it gets to you when you are at the pharmacy. To get that understanding of ‘how is this produced?’.” (D04-1)	Give an understanding of drug production and the test and controls the drugs must go through
Quality control/assurance	”All of us that will work in the industry [medicinal industry], we will think back on Analytical Chemistry and think – ‘This machine: I’ve tried that in Analytical Chemistry’” (D05-1) “It’s extremely important, especially if you have to work with quality control or production or – there is HPLCs everywhere! You have to use it when you get out. Suddenly you are asked to analyse a sample for this and that, how will you do that? If you haven’t learned how to do it, it will be a big problem.” (D08-1)	To be familiar with instruments and analytical methods. To practice manipulative skills.
Researcher	”Such basic things in the laboratory are important because then we are able to work in research afterwards” (D11-1) ”Maybe someone would like to be a researcher, then the laboratory is a big part.” (D16-3)	To be familiar with the instrument and the procedures in the laboratory.
Medicinal industry	”By being in the laboratory, I think we get much better insights in to how it really is in the companies out in the real world” (D05-3) “So, therefore it does not help to just learn it theoretically… if we had to go to the industry afterwards and try to actually produce it” (D06-1) ” Well, again it’s about being competent enough to do this effectively in the industry. It is a skill we need afterwards.” D06-3	To learn skills and procedures to gain a background understanding for the process. Practical skills are also important.
Pharmaceuticals	”In our sector, then it is, well… often… well, we should be able to stand in the laboratory and develop drugs and such things” (D01-3) “A lot of us will end out with manufacturing or quality assurance or whatever it is that we should do, right” (D07-3)	Practical skills
Desk job	“It might be that many of us, pharmacists, we end up at a desk job or similar. But I still believe that it matters that we know how complex it is [drug development]” (D02-3)	Understand the complexity of the process of drug development and the processes of laboratory work.

Other affective experiences

The students are engaged affectively when they are in the laboratory. As described in Paper 1, affective measures are psychological constructs such as values, attitudes, beliefs, perceptions, emotions, interests, motivation, and the like. From the interviews with the students, it seems clear that the affective domain plays a key role in the learning situation in the laboratory. Here a student describes how much motivation affects the learning experience in the laboratory:

> *"Lab work is really about being motivated to do it properly, and – well it's not just something you should read by yourself, it is actually a thing where someone else is dependent on your work. There are days where you are more motivated and then of course it is better to be down there (in the lab) compared to a day where you are a bit "urgh!" Then you don't get as much out of it, because maybe you don't keep up with what you are doing and why you are doing it, but you just follow the manual like you did in high school." (D16-1)*

From this quote, the student mentions three distinct aspects. First, the student feels that being successful in the laboratory is more related to one's attitude or motivation than actual skills. Second, the lab work requires the students to work in groups and collaborate, and they are responsible for their group members (and themselves). Lastly, the learning experience in the lab is associated with metacognitive activity and reflection or described as *minds-on* instead of *hands-on* by "just" following the instructions

Thus, affective measures hold the potential to either completely ruin an experience in the laboratory or significantly improve it. Flathery (2020) finds in the review from 2020 about affective chemistry research that qualitative research in this area is limited. Based on the description from the student above, affective measures, such as interest and motivation, seem to hold the key to the quality of students' learning experience in the laboratory. Further research into this area would be interesting. The importance of the affective dimension is also stated by Galloway and Bretz (2016); they find that students act differently on the same experiences dependent on their affective experiences in the laboratory, providing different affordances for learning. The affective experience of the lockdown definitely influenced the students' experiences. Through interviews conducted with students during the lockdown, it became evident that they underwent a sort of emotional shock (which, I believe, many of us experienced to some extent). This situation profoundly impacted the students' overall experience, as they faced significant uncertainty and discomfort resulting from being abruptly removed from their daily routines and social lives. These experiences undoubtedly profoundly influenced the students and were predominant in their descriptions, leading to strikingly similar accounts of feeling disconnected from the laboratory environment.

Methodological considerations on Paper 3

In this section, I will provide further considerations to the methods applied in Paper 3 (methodological considerations related to Paper 2 can be found in the next chapter). I will elaborate on the choice of thematic analysis and the strengths and limitations of this method and add some considerations on the theoretical aspects of the thematic analysis.

Thematic analysis, as used in Paper 3

Thematic analysis is a versatile method of analysis and can be independent of a theoretical framework. In my perspective, this is one of the significant strengths of thematic analysis.

Further, it is well suited for describing thoughts, experiences, or actions across a data set, seeking common or shared meanings (Kiger & Varpio, 2020). The common and shared meaning and experience of being without a laboratory was exactly the case in my analysis.

In thematic analysis, there can be different approaches to the data and different levels of interpretation. Braun and Clarke (2006) distinguish between *inductive* and *deductive* thematic analysis. In the inductive thematic analysis, the themes arise from the researcher's data and can be quite different from the researcher's initial interest. Whereas in a deductive (or theoretical) analysis, a certain theoretical framework shapes and decides the themes the researcher looks for. During my data analysis, I used both inductive and deductive approaches. I used an inductive approach initially, primarily because I had studied the phenomenographic approach prior to these interviews. The phenomenographic approach explores qualitative differences in the students' experiences and is indeed inductive.

Nevertheless, to my surprise, there was extraordinarily little variation in how the students described their experiences in the "Covid lockdown" interviews (from March 2020). In this way, the data and the emerging themes were unexpected. During my analysis and description of the themes, I found a theoretical framework, which provided me with a key to understanding what was recurrently expressed by students in the interviews. The theoretical framework guided the second round of coding with a deductive approach. The theoretical frameworks I used to explain and support the themes of my analysis were feedback, scaffolding, the embodiment in science education, and the description of science practice as text production.

Theoretical considerations for Paper 3

Students struggling to explain what was at stake in the laboratory characterised the themes regarding the epistemic importance of the laboratory. Therefore, the notion of embodiment and the perspective of Latour and Woolgar (1986) on scientists' work as text production were used to describe what is at stake in the laboratory.

Embodied knowledge

Embodiment centres on the role the body plays in learning. Researchers in science education have started to acknowledge the importance of the body in science learning (Kersting et al., 2021). Many different ways of addressing bodily knowledge and embodiment exist. Examples are tacit knowledge, embodied knowledge, image schemas, and embodied cognition.

Embodiment encompasses experiences that arise because we have a body, and our bodily experiences shape our experiences of interacting with the world. Four senses of embodiment are described by Kersting et al. (2021); here, I will make a brief description of the four senses of embodiment. Later I will relate my findings on the importance of embodiment to these four senses.

The **physical sense of embodiment** focuses on structures or schemas. These structures arise from our perceptual and motor systems and general body-based experiences. The structures support or shape the cognitive processes. One such structure could be *conceptual metaphors* (Lakoff & Johnson, 1980, p. 7). The way we think about phenomena in the world is highly influenced by how we experience and interact with the world with our bodies. According to Lakoff (1987, p. 267), our early bodily experiences give rise to the formation of so-called "*image schemas*" that direct the way we think about and give structure to concepts. Such image schemas underlie widely used conceptual metaphors such as "Life as a journey." In this metaphor, an underlying image schema is at play derived from the bodily experience of moving through space from a starting point to a target. The conceptual metaphor, in turn, is used to make new expressions about what is not immediately understandable (Lakoff & Johnson, 1980, p. 77). The metaphor can help us understand (aspects of) life, with a beginning and an end, detours, delays, and a final destination. The physical sense of embodiment can help us connect the inherently abstract concepts of science to bodily structures in science education.

The **phenomenological sense of embodiment** focuses on the lived experience. Science is very much a practical endeavour carried out by human beings in specific circumstances. Even though scientists may think of themselves as objective spectators of the world and then describe it – that is not an accurate description of how knowledge comes into being. Scientists engage with the physical world in their experiments. These experiments demand many actions from the scientist, making the body an inquiring and researching body. We, as humans and scientists, experience the world through the body. Hence, our bodily movements and experiences are our access to the world and determine how we experience the world. Hence, the phenomenological sense of embodiment highlights that authentic bodily experiences are essential in science education.

The **ecological sense of embodiment** is concerned with the body and environment interaction. Interaction with the world around us is important in science education and laboratory teaching. Together with mind and body, the environment enables and restricts the body's actions and hence cognition. In the laboratory teaching environment (especially instrumental analytical chemistry), one of the important purposes of the session is the interaction with instruments or chemicals. The instruments offer different affordances for learning, as Bernhard, (2018) shows, where physics students learn various aspects of 'the same physics' depending on the instrument available.

The **Interactionist sense of embodiment** focuses on the importance of collaboration and interaction. The focus is on how meaning and thinking (e.g., problem-solving) arise through interaction and the social and cultural contexts. The laboratory has the potential to enable collaborative social interactions. Through these interactions, students and their teachers can engage in collaborative inquiries, and the classroom can function as a community of scientists (Hofstein & Lunetta, 2004).

These different senses of embodiment are all present in science and laboratory teaching. What makes embodiment challenging to describe is that often, it extends beyond our ability to explain it in words. We can call it intuition, fingerspitzengefühl, or tacit knowledge. It is those things we struggle to explain and hence are difficult to teach. Polanyi describes tacit knowledge as something implicit and something one knows without explaining why. The example he uses in the book, the "Tacit dimension," is people's ability to recognize faces (Polanyi, 1966, p. 4). Few can explicitly describe why they recognize someone; however, we are entirely sure as soon as we see them. It could also be skilled scientists' bodily knowledge about how to tilt a pipette correctly – however, they would probably not be able to describe exactly what they are doing.

Polanyi further states that true learning involves using what we have learned (Polanyi, 1966, p. 17). Knowing how to describe our embodied or tacit knowledge is less important. We might not be able to access all of our knowledge consciously. It might be stored in nonverbal formats (like pictures or smells) or even as unconscious biases that direct our actions without much thought (Brock, 2015, 2017). This makes this form of knowledge extremely difficult to report because of the implicit nature of the knowledge (Taber, 2014). Nonetheless, we find that the embodied experience is an essential dimension of the students' laboratory teaching experience.

The three structures I describe in paper three all relate to the phenomenological sense of embodiment described by Kersting (2021). This sense of embodiment is rooted in students' experiences as humans and being physically present in the laboratory, influencing the objects at hand. Specifically, the *temporal structure* of embodiment is inherent in the phenomenological sense, as it describes a sequence of actions following a defined order. The phenomenological sense of embodiment is also inherent in the *narrative structure*, since it depicts how students' physical presence in various laboratory areas enables them to recount their interactions with different instruments and objects, creating a narrative for themselves. In addition, the *narrative structure* develops into a *physical sense of embodiment*, dependent on the strength of the narrative, the laboratory exercise, and the students' own narrative and identity. Kersting's description of the ecological sense of embodiment is also present in the laboratory and is related to the *causal structures* described in Paper 3. The instruments in the laboratory play a significant role in the type of learning students can acquire (Bernard, 2018), thereby invoking the ecological sense of embodiment. The transformations facilitated by the instruments provide students with an experience of *causal structur*es, illustrating that altering instrument settings lead to specific changes.

"An anthropologist visits the laboratory"

In the book "Laboratory Life," Latour & Woolgar (1986) describe a research laboratory from the viewpoint of an anthropologist – a scientific outsider. The anthropologist describes the process of scientific work as the production of text. Looking at our data with this perspective of "science as text production," we describe the important perspective this understanding gives us of the students' experiences in the laboratory. Here, I present a few more details about the anthropologists' visit to the laboratory.

In the laboratory, the anthropologist notices two distinct areas. The office space with only books and paper(s), and the benches (laboratory space) with many specialized instruments (Latour & WooIgar, 1986, p. 45). People in the office sections are seen reading, writing, and discussing. Sometimes, they join their colleagues at the bench area, where people do different things such as sewing, cutting, mixing, screwing, and shaking. This division is also present in the teaching laboratory of analytical chemistry, where students mix and weigh-off materials in designated areas and discuss and write their reports in others. The anthropologist describes the laboratory as a place juxtaposing two kinds of literature. One type of literature originates outside the laboratory (published in scientific journals), and one originates inside the laboratory (Latour & WooIgar, 1986, p. 47). The text from inside the laboratory is *literary inscriptions* such as graphs, data points, and the like coming from *inscription devices* and series of transformations. These transformations are the "magic" and the hard work of the science laboratory. Usually, researchers have some material of interest, e.g., a receptor in a rat's brain or the amount of a drug in a pill. Through various manual actions (crushing, shaking, extracting, etc.) and transformations through inscription devises (HPLC, GC, UV-Vis absorbance, weights, volumes, etc.), the scientists can argue about how the receptor works or the amount of drug in the pill.

Scientists are, in this way, readers and writers. However, they read and write quite differently than, e.g., novelists. Their reading and writing all emanate from the laboratory. Precisely how the different activities in the laboratory combine to be a written product is the process of the research laboratory. In the same way, students in the teaching laboratory learn to understand how the texts are built and how to make a scientific argumentation based on the literary inscriptions from the laboratory. In paper 3, I argue, based on this description of the laboratory as a place for text production, that experiencing and participating in the transformations that occur in the laboratory is important for developing understanding scientific argumentation.

In discussing the laboratory as a site for text production, Latour and Woolgar approach the subject as scientific outsiders and take great care to avoid making assumptions about the true meaning of their observations. However, as a chemist, I am an insider and more willing to make assumptions. I find their description of scientific work and observations of transformations to be highly significant, as it aids in understanding the "magic" and hard work that goes into scientific arguments. Latour and Woolgar describe a research laboratory, and I utilise their descriptions in a teaching laboratory. The two environments can be compared; in teaching, we seek to create authentic situations to prepare students for future scientific work.

Consequently, many teaching laboratories resemble research laboratories. One feature that Latour and Woolgar describe is the back-and-forth movement between the office space and the laboratory. The analytical chemistry-teaching laboratory has designated office and laboratory spaces to facilitate this movement. The office spaces consist of available workbench places and groups of tables in adjacent rooms. This setup allows students to move between distinct areas where they can analyse and work with the data generated in the laboratory. By describing the laboratory as a site for text production and the process of moving between office and laboratory spaces, there is an answer to the question, "What is laboratory teaching?". Laboratory work does not cease when one leaves the laboratory, and both proper preparation and reporting of work done in the lab are crucial. This is an area where teaching laboratories could be improved, as evidenced by the study conducted by Galloway and Bretz (2016), where students only reflected on their performance and chemistry in the laboratory during their interviews. The laboratory teaching experience should be clearly connected with pre- and post-lab activities, emphasiing the importance of preparation and reporting (Agustian & Seery, 2017).

Conclusion

In Paper 2, the phenomenographic analysis revealed two distinct ways in which students experienced the laboratory. Despite being untraditional in phenomenography, utilising the congruence model as a theoretical framework proved helpful in describing variations in students' perceptions and understanding of the significance of congruence areas. This approach shed light on how students experienced a range of factors that influenced their overall laboratory experience. Notably, the analysis highlighted that students' perception of time substantially impacted several other aspects of laboratory teaching, underscoring the importance of considering students' affective state of mind while engaging in laboratory activities.

Using thematic analysis in Paper 3 provided an opportunity to explore the experiences of students who were not physically present in the laboratory. This approach offered valuable insights into the essential aspects of education that the laboratory provides. Through thematic analysis, I identified themes that held significance for the students. By incorporating theoretical considerations, I gained a deeper understanding of their experiences while also pinpointing factors that influenced their experiences.

Introducing Latour and Woolgar's (1986) concept of the laboratory as text production through thematic analysis shed light on the students' struggles in comprehending data when they had not actively participated in its production. Moreover, it allowed me to describe how the physical environment structured the students' experiences and contributed to the formation of crucial embodied structures that supported their understanding.

Furthermore, thematic analysis underscored the importance of informal learning situations, where teachers acted as scaffolds for students' thinking and served as scientific role models. This aspect emphasized the significance of teacher-student interactions beyond formal classroom settings.

In summary, employing thematic analysis in Paper 3 facilitated a comprehensive exploration of students' experiences, provided theoretical insights, and highlighted the significance of both the laboratory environment and informal learning situations in shaping their learning journey.

In this chapter, I have discussed a range of factors that shape pharmacy students' experience of laboratory learning, both from existing literature on chemistry and pharmacy students, from general university pedagogy perspectives, and my empirical work. Among the central factors discussed are:

- Students' conceptions of time and approaches to learning – these two factors are closely related.
- Assessment and how the type of assessment can influence student approaches to learning
- Feedback and scaffolding and the importance of timely and informal feedback in the laboratory, together with teachers' pedagogical competence and approach to teaching
- Embodiment and transformation of knowledge and how these factors provide embodied structures that lay the foundation for epistemic understanding and scientific judgement
- Students' conceptions of professional identity, how pharmacy students relate to several different potential future identities in the lab work setting.
- Affective elements such as motivation, anxiety, self-efficacy, and others.

4 – Theory-practice relation in the laboratory – Paper 4

This chapter relates to the third research question, "How do second-year pharmacy students experience the role of laboratory work in the theory-practice relation?" Paper 4 answers this question, so here I will elaborate a little further on the phenomenographic research approach used in Papers 2 and 4 and provide some methodological considerations.

Phenomenography

The research object in phenomenography is a phenomenon or concept being studied to understand the diverse ways people experience and understand it. The goal is to explore the qualitative variation in individuals' experiences and perceptions of the phenomenon. Phenomenography focuses on uncovering the distinct categories or ways of experiencing the research object rather than seeking to explain why those variations exist. The emphasis is on describing the range of qualitatively different ways individuals interpret and make sense of the phenomenon. For example, in educational research, the research object in phenomenography could be the learning process, a specific teaching method, or a particular educational concept. Researchers would aim to investigate and describe the diverse ways learners understand and experience that phenomenon. By identifying the various categories of experience, phenomenography provides insights into the variations in individuals' interpretations and helps deepen our understanding of the phenomenon under investigation.

Phenomenography applies what Marton (1981) calls a *second-order perspective*. He describes the differences between the first and second-order perspectives:

> *"In the first and by far the most commonly adopted perspective, we orient ourselves towards the world and make statements about it. In the second perspective, we orient ourselves towards people's ideas about the world (or their experience of it), and we make statements about people's ideas about the world (or about their experience of it)."* (Marton, 1981)

Phenomenography works on the principle that people's experiences and understandings of the world are diverse. Yet, there is a limited number of qualitatively different ways of experiencing a phenomenon, which can be classified into categories of experience (e.g., Trigwell, 2006). The primary aim of phenomenography is to recognise and describe these distinct ways of experiencing a phenomenon to better understand the differences between the students' experiences. Addressing these differences can enhance teaching and learning.

The empirical data from phenomenographical studies are typically individual interviews with a sample of people who have experienced a particular phenomenon (Hasselgren & Beach, 1997), such as here a specific laboratory-learning environment. The interviews are analysed to identify the different ways in which people experience and understand the phenomenon, and these experiences are then organised into a hierarchical set of categories or levels of description. These are referred to as the outcome space. The hierarchical structure of phenomenography is based on the idea that experiences and understandings of a phenomenon can be grouped into levels of complexity or abstraction (Marton, 2014, p. 116). These levels of description typically range from more concrete and specific experiences to more abstract and general understandings. There are several ways to develop an outcome space. One approach involves a *hierarchical structure*, where categories are logically organised to incorporate lower-level perceptions within higher or more advanced ones (e.g., Eckerdal, 2015). Alternatively, an outcome space can be designed as a *developmental progression*, wherein each subsequent perception is considered superior or more desirable than its predecessor (e.g., Burrows et al., 2017).

In Paper 2 and 4, my primary focus lies in exploring the diverse ways students experience their learning in the laboratory. Therefore, the second-order perspective of phenomenography is a suitable analytical framework because, through this approach, we can obtain a "statement about people's conception of reality"(Marton, 1981).

Experience and understanding

Experience and understanding are intricately connected in phenomenography. Experience is a central concept in phenomenography because the experiences of phenomena are the object of research. Your experience leads to the understanding you get. The qualitatively different ways of experiencing a phenomenon arise because of the *intentionality* of human behaviours (Han & Ellis, 2019). This *intentionality* is why people, who experience the same phenomenon, will arrive at different understandings. The experience depends on your intentions or purpose and where you send your focus of awareness. This two-sidedness, intention on one side and awareness on the other, is called the *anatomy of experience*, and differences in intention and awareness give rise to variations in experience (Marton & Booth, 1997, p. 87). In a way, this intention is captured in the aspiration and background category of the congruence model and highlights the importance of previous experiences. For instance, in the study by Galloway and Bretz (2016), students who showed interest in the subject tended to have better experiences and acknowledged their learning process in the laboratory. In contrast, students either intimidated by the expensive glassware or frustrated by their inability to follow the manual tended to experience not learning anything.

Experience is built on two components of conscious awareness. The *referential aspect* and the *structural aspect*. They are simultaneous and mixed. Your experience's nature is determined by what part of these aspects come to your awareness. The referential aspect is concerned with the meaning of the experience and what it takes to create meaning. The structural aspect is concerned with the parts of the experience and their relationship. The structural aspect is further divided into an *external* and *internal horizon*. In Paper 4, we only distinguish between referential and structural aspects, but the structural aspects are dependent on both the internal and external horizons. The external horizon is how the parts of the experience differentiate themselves from the context and the background. This can both be a concrete and material background, such as a laboratory equipped with a lot of instruments, or a more abstract metaphorical context, such as “scientists are smart” or “being afraid of dropping glassware on the floor” (Marton & Booth, p. 89). The internal horizon is how parts are distinctive but form a cohesive entity and their interrelationship (Han & Ellis, 2019; Marton & Booth, 1997, p. 87). The example Marton and Booth provide in the book “Learning and Awareness” is about a deer in the forest at dusk. I would like to translate this explanation of the different structural aspects of the experience into an example in the teaching laboratory.

Imagine an exercise in the analytical laboratory where you must prepare some samples and analyse them by HPLC. The referential aspect of this exercise could be that the samples originate from a drug, and as a pharmacist, you should be able to guarantee its quality. On the other hand, you could also perceive this as an exercise you must perform to pass the course. This could depend on your goals as a student (DeKorver & Towns, 2015, 2016). The structural aspects are all the various parts of the exercise, e.g., the surrounding environment of the teaching laboratory, the HPLC instrument, and all its parts, e.g., mobile phase, stationary phase, detector, injection method, or the underlying theoretical concepts. The external horizon of this experience is all the irrelevant objects in the lab, e.g., the sinks, the doors, the fume hoods, and other instruments not important for your exercise or an upcoming exam in another course. The external horizon of the structural aspect likewise affects how the analytical laboratory distinguishes itself from the organic and physical chemistry labs, or it could be an abstract context such as “wanting to finish early.” The internal horizon is the procedure for preparing your samples to fit the analytical method in the exercise. It is how the injection method affects your data and limitations, together with the uncertainties you get dependent on your detection method. It could also be how one spectrum differs from another, depending on the type of analysis and the sample.

The learning you can gain from experience is dependent on where you direct your focus of awareness. Students are different and have different prior experiences to draw upon in teaching situations; therefore, they end up with different understandings. In the teaching situation, teachers try to modify, strengthen, or change the students’ conceptions. There is a strong connection between the students’ awareness and cognitive load theory. In cognitive load theory, *extraneous* and *intrinsic cognitive loads* are distinguished. Intrinsic load is a natural process encountered when tackling new mental tasks. In contrast, extraneous load, prominent in the laboratory setting, arises from factors like unfamiliar surroundings, instrument noise, safety considerations, and group work. Here it is important how students focus their awareness. Excessive extrinsic overload limits the capacity for intrinsic cognitive load necessary for learning new concepts, meaning that students are overloaded with inputs from the learning environment limiting their mental capacity to focus on learning (Tuovinen & Sweller, 1999). A common way to overcome students' cognitive overload is to prepare pre-laboratory work (Agustian & Seery, 2017), that helps the students prepare before entering the laboratory. In this way, teachers can try to direct the students’ focus of awareness by creating pre-laboratory experiences that will affect the students’ experience in the laboratory.

In educational contexts, some ways of understanding and seeing a specific situation are more powerful than others, and acquiring these more powerful ways of conceiving situations is the goal of teaching. As Marton puts it:

> *“How you can possibly solve a certain problem reflects how the situation or the problem appears to you—what you notice, what you attend to. How you handle a phenomenon that you encounter depends on what you see it as, what it means to you and what it appears to be. After all, in a particular situation, we always act according to the way that situation is perceived by us.”* (Marton, 2014, p. 85)

The learning environment and types of examples the teacher chooses are important for the experience and the conceptions the students gain from the teaching. The teaching laboratory provides a special learning environment. The examples and problems students encounter are different from what they experience in a theoretical lecture or dry problem-solving class. In the laboratory, students can experience features that might seem irrelevant in other situations. Examples could include learning how to handle a pipette effectively, understanding the significance of 1 gram of a compound in different contexts, or recognizing the importance of proper mixing techniques. While these aspects may appear insignificant or unimportant when reading a manual or instructions, they become crucial for generating reliable and usable data during the actual execution of the experiment. These experiences are critical for the students to experience and relate to earlier experiences because learners' earlier experiences are important for their sense-making in new experiences (Marton & Tsui, 2004, p. 21).

Methodological considerations about Papers 2 and 4

Interviews

In phenomenographic studies, interviews are the most common data type. Typically, the interviews are semi-structured (Hasselgren & Beach, 1997), meaning they are open, leaving plenty of room for the participants to elaborate on their experiences while focusing on a specific phenomenon. In this project, my focus is on the laboratory as a learning environment. My project and the interviews I have conducted are very explorative in nature. I wanted to investigate students' experiences of the laboratory teaching and learning environment. The students describe many aspects of their learning experience in the laboratory.

In the interview guide, the interviewer prepares open questions about the phenomenon of interest. In the interview guide for both data collections in Papers 2 and 4, I used the congruence model to structure my interview guide. It is unusual in phenomenography to use a theoretical model to guide the interviews. Usually, a more open approach is used, meaning that the researchers produce their own open questions about the phenomenon of interest. I used open questions to obtain rich descriptions of all aspects of the students' experiences in the laboratory. Even though it is unusual to use a theoretical model to inform your interview guide, I found it was assuring that I touched upon all the congruence areas to ensure that the entire laboratory experience was captured in the interviews. However, it is important to distinguish between research and interview questions when interviewing. In the interview situations, you do not pose the research question directly to the participant. Still, you make several interview questions where the answer might point towards answering the research question (Kvale, 2007, p. 62). Except for the end of the interviews for Paper 2, where I showed the students a translated congruence figure, the students were unaware that I asked these questions because of some theoretical construct.

As argued above, I do not think the students would have answered differently in any of the interviews if the interview guide had been constructed without the congruence model in mind (except for the part where I directly asked students about the congruence model in Paper 2). I will argue that using the congruence model in shaping my interviews was only helping me to pose good questions about their experiences of the laboratory environment. However, I, as a researcher, have been affected by the congruence model in the way I think about laboratory experiences. Moreover, this is evident in the results in Paper 2. In phenomenography, having an open mind when analysing the interviews is important. The researcher should be open to slight differences in the students' statements and findings outside of what is anticipated. This can be difficult, and why some sort of interrater reliability helps validate findings in this type of research. Therefore, when employing the congruence model to shape the interview guide and, as in Paper 2, to analyse it, there is a concern that it could become a self-fulfilling prophecy. It is important to consider the potential risk that the research findings may simply mirror my preconceived notions (Hasselgren & Beach, 1997). This critique, often directed at phenomenography, should be considered when analysing the data. The "laboratory as a learning environment" as a phenomenon is broad, and the congruence model (Hounsell & Hounsell, 2007) helped discern essential aspects of the phenomenon. Overall, the researcher defines categories of different experiences through the phenomenographic analysis, and these categories are compared with each other to describe structural and referential differences. In Paper 2, I introduce two categories; however, it can be argued that my presentation of these categories does not sufficiently consider their structural and referential aspects. Instead, I focus more on the various ways in which students experience different congruence areas. This deviation from an essential element of phenomenography raises questions about the classification of the findings in Paper 2 as phenomenographic. However, as I see it, the two experiences of time presented in Paper 2, the experience of time in the laboratory as a "waste of time" and a "time for reflection" seem to represent the two well-defined approaches to learning surface and deep approach, respectively. Further, the congruence model represents different structural and referential aspects of the laboratory experience. An example could be the congruence area of "course organisation and management". This is a referential aspect setting the scene for the laboratory course. Further, the teaching-learning activities can be seen as structural aspects of the laboratory experience. These activities should create meaning; however, for the students experiencing the laboratory as a waste of time, this does not happen.

The interviews for the two papers were quite different. In Paper 2, the interviews were about 40-60 min long, and they were held in August after the students had the course pharmaceutical analytical chemistry in the spring of the semester before. The course was, therefore, not currently present in their minds, and at the time of the interviews they were engaged in other laboratory courses – this makes the students prone to compare the analytical chemistry course to other laboratory courses. On contrary, the interviews for Paper 4 were held during the course. Here I also have two interviews with each student. One at the beginning of the course and one at the end shortly after the exams.

A pool of meaning or excerpts in a context?

It is common to have data transcribed verbatim when analysing data in phenomenography. There are different approaches to the analysis of transcribed interviews (Collier-Reed & Ingerman, 2013). One way is to go through the transcripts and mark all areas of the transcripts where students mention the phenomenon in question and then pile them into a pool of meaning. From this point onward, the rest of the analysis is based on this pool of meaning. A different approach is to consider only parts of the interview but keep the broader context. A third approach only considers interviews as a whole (Collier-Reed & Ingerman, 2013). Below I will describe how I used the data during different stages of the analysis process.

Analysis process

There are various stages in the analysis process. Han and Ellis (2019) present differences in phenomenographic analysis processes. Some of the described processes have four stages in the analysis, and some have seven. In both Papers 2 and 4, the first stage of analysis was to familiarise myself with the data. I read and reread the interviews to get familiar with the data material. Sometimes I also listened to the audio recording of the interviews, some in full lengths, some in parts. During the familiarisation process, I got an idea of interesting aspects of the phenomenon and identified some areas to analyse further. For paper 4, the amount of data was huge; therefore, I wrote small summaries of the interviews called profiles. In this stage, I used the interviews as a whole. During this process, the amount of data was overwhelming, and it was impossible for me to cope with "the laboratory as a learning environment" as the sole phenomenon. Therefore, I identified aspects of the phenomenon like "time" in Paper 2 and "theory-practice" in Paper 4.

After the familiarisation stage, I identified the data related to the students' conceptions of experiences in the laboratory with a focus on the different aspects of the phenomenon identified in the previous familiarisation stage; this process is called identification. I identified relevant parts of the interviews to all the aspects of the phenomenon in each data set. For Paper 2, I chose to focus on the students' experience of time in the laboratory, and for Paper 4, I looked at the students' experience of theory and practice relations. I then returned to my data set to secure that I had identified all the places where these themes were mentioned. I marked all the excerpts from the students' interviews and created pools of meaning from these excerpts.

In the next stage called sorting, the pool of meaning was sorted into different categories based on similarities. Sometimes, I doubted the context of the excerpts in the pool of meaning and returned to the interview as a whole or the related parts of the transcripts to ensure I understood the meaning in the context. From the sorting stage, several groups, with each a pool of meaning, emerged. For example, in Paper 2, I had aspects of laboratory experience such as time, group work, and affective experiences; in Paper 4, examples of aspects could be: contact with the teacher, preparation for lab, and study environment.

The next stage could be called contrasting and categorising. Here I started to describe the emerging categories, some were merged, and others were split before forming the final categories. In Paper 2, I used the congruence model to distinguish the two categories from each other. In paper 4, I investigated the differences between the categories and tried to define the structural and referential differences in the experiences. It is worth noting that these structural and referential aspects are analytical constructs and are made for us as researchers to distinguish between different research points of view. The constructs are not separate entities but parts of a whole (Marton & Booth, 1997, p. 85).

Validity

In qualitative research, the concept of saturation in data collection serves as an indicator of sample quality (Fusch & Ness, 2015). However, it is important to recognise that there is no universally applicable approach to achieving saturation in qualitative methods. Fusch and Ness (2015) comprehensively describe saturation, highlighting its dual nature as rich in quality and thick in quantity. My interview guide effectively elicited insightful and comprehensive responses from the participating students, demonstrating the richness of the data collected. However, the quantity of data collected was constrained by the limited number of students who volunteered to participate (for discussion on recruiting, see Chapter 3). When doing phenomenography, you want to capture the broadness of the experience of the phenomenon. The goal is not to interview the average student but to get the broadest description of the phenomenon. Therefore, you aim to interview the students with the most diverse experiences. In the interview situation, you aim for the point of saturation. Saturation is achieved when new interviews or data collection do not yield any significant or substantial additional information or insights. In other words, researchers reach a stage where they begin to hear repeated themes, concepts, or patterns in the data, and further interviews or data collection do not contribute to their understanding. I had only six participants in the study for Paper 2, and this is a real limitation of the study. In my experience, I felt some aspects of the laboratory experience had reached saturation. Still, with so few students I cannot know, and if it had not been a pilot study, I would have aimed for more participants. Even though I only had six participants in the study for Paper 2, I felt that the students I interviewed had quite different experiences and were more diverse than the 16 students I interviewed for Paper 4. The reason I experienced this could be the recruitment method, where Paper 4 relied on volunteering and Paper 2 persuasion, but it could also be that COVID-19 and the lockdown of the university "tainted" somehow the students' experience to be more aligned because of this untraditional event. In Paper 4, I experienced that no new themes emerged in the last interviews, and this lack of new themes indicated saturation.

In phenomenography and qualitative research, in general, the researcher is a part of the analysis. If someone else had the same empirical data, there is no reason to believe they would formulate the same categories. However, the strength of phenomenography and an essential part of the validity check is that other researchers or practitioners can recognise the descriptions of the categories. To ensure reliability in our analysis, we employed a dialogic reliability check method, as advocated by (Åkerlind, 2005). This approach involved extensive discussions among the researchers, where each researcher presented their interpretive hypotheses and engaged in critical evaluation. Through this collaborative dialogue, a consensus was reached based on mutual agreement. We opted for this method instead of using an interrater reliability measure, which is increasingly common in chemical education research (Watts & Finkenstaedt-Quinn, 2021). It is worth noting that an interrater reliability check can sometimes provide limited information since categories are described at a collective level, individual statements may not fully capture the essence of a category, and certain statements may encompass traits from multiple categories (Sandbergh, 1997).

Conclusion

In Paper 4, I examine the experiences of students enrolled in the Pharmaceutical Analytical Chemistry course regarding the relationship between theory and practice. Through phenomenographical analysis, I identify three distinct conceptions labeled A, B, and C, representing different levels of sophistication. These conceptions form a hierarchical structure, with conception A being the least advanced and conception C being the most advanced.

Conception A portrays the laboratory experience as a visual representation of the theoretical concepts. Students in this category believe that the visual impressions they gain from the laboratory activities assist them in memorising the concepts and theories.

Conception B views the laboratory experience as an opportunity to engage in a multimodal environment that supports the acquisition of theory. In this conception, students follow specific procedures, interact with instruments, and actively generate data. They perceive the laboratory as a space to apply chemistry principles, facilitating their understanding of theory. The hands-on experience enhances their engagement with theoretical concepts.

Conception C considers the laboratory experience as a complementary perspective that enhances the understanding of theory. Students who hold this conception emphasise the value of learning from mistakes and dealing with problem-solving in imperfect situations. They recognise that encountering challenges and addressing them during laboratory activities contributes to a deeper comprehension of the underlying theory and the relation between theory and practice.

I cannot say this is a complete list of students' conceptions about theory and practice relation. It would be interesting to see if not more or somehow different conceptions would emerge if another type of course, e.g., organic chemistry was investigated. The theory-practice aspect of laboratory teaching emerged from my interview data; it was not something I specifically asked students. I do not think many students consider how theory and practice relates, but I find it could be beneficial to make this aspect more explicit in laboratory courses, and this is where the teachers have a say. Further, I think the laboratory teaching discussion would benefit from teachers investigating their own and colleagues' understanding of the relation between theory and practice.

Concluding thoughts

> *"To experiment is to create, produce, refine, and stabilize phenomena. [...] there are endless different tasks. There is designing an experiment that might work. There is learning how to make experiments work. But perhaps the real knack is getting to know when the experiment is working."* (Hacking, 1983, p. 230)*]*
>
> *"Between an abstract symbol and a concrete fact there may be a correspondence, but there cannot be complete parity; the abstract symbol cannot be the adequate representation of the concrete fact, the concrete fact cannot be the exact realization of the abstract symbol[..]" (Duhem, 1914/1991, p. 151).*

In this thesis, I have explored students' outcomes and experiences of learning in chemical and pharmaceutical laboratories. I have presented a general perspective of student outcomes of laboratory learning experiences in higher chemistry education (Paper 1) and discussed specific factors influencing student learning in the analytical chemistry laboratory (Papers 2 & 3). During my interviews, I have talked to students both about their experiences of learning in the laboratory, and about their experiences when the laboratory disappeared. A recurrent theme in the interviews was the students' view of the role of the laboratory experiences in relating theory and practice (Paper 4). It is surprising that students so often bring up the relation between theory and practice, because (as shown in Paper 1) there are so many other outcomes of laboratory learning besides the theory-practice connection.

Considering the five clusters of outcomes described in Paper 1, we might take the terms "theory" and "practice" and relate these terms to disciplinary knowledge and competences one the one hand and experimental knowledge and competences on the other. I think the students refer to something more than what these two clusters describe when they refer to theory-practice relations. As described in Paper 4, the way the students use the term "theory" is broad. They are both referring to central concepts or relations, and at other times they are referring simply to the text in the protocol as "theory." Perhaps a better way of describing what they are saying is to distinguish between the "ideal" on the one hand and the "real" (or "material") on the other.

Thus, in both Papers 3 and 4, students describe how their laboratory experiences help them understand the relationship between the real and the ideal, for instance, by making graphs of the material samples they are exploring or when they are using a protocol to help them conducting an experiment. Through my work on Papers 3 and 4, I have seen the students' understanding of the connection between the real and ideal as the central learning outcome from their laboratory experiences. By employing the terms "real" and "ideal" rather than "practice" and "theory" I am making clear that this overall outcome is related to all the clusters of outcomes presented in Paper 1 and not just the two clusters of disciplinary learning and experimental competence. I believe that understanding the relation between the real and ideal may lead to learning outcomes within all the different clusters, including the epistemic, affective, and transversal outcomes.

Further, with the “real” and “ideal” I want to associate the words with a philosophical understanding of science where there is a focus on the differences between the material world and the models, we use to describe it, as illustrated by the two quotes from Hacking and Duhem above. It is primarily within the laboratory setting the students encounter and interact with the relationship between these two sides of science.

I am influenced by Ian Hacking’s description of science as “representing and intervening” (Hacking, 1983), recognising that abstract concepts of theory or models are nothing without the experiments, the material, and the physical world. Theoretical constructs are only valid and useful in science if they have some sort of predictable or explanatory power of phenomena in the material world. In science, this “material world” is often in very controlled conditions in the laboratory. Controlled conditions are necessary for our theories to work at all. And even in these controlled conditions, it can be hard to make experiments work.

In the same way, experiments can only say something general if they are performed correctly, designed well, and repeatable. In the laboratory, we can create such stable conditions, but it is demanding work. The students in the laboratory need to understand how the “material world” relates to our descriptions of it – and how the real and the ideal restricts, enrich, and unfold each other.

I propose that the primary outcome of laboratory learning is to foster an understanding of how theoretical concepts, models, and ideas shape and influence experimental setups and experiments and how experiments impact, support, modify (or "resist”) our theoretical constructs. Based on the research presented in this thesis and my three overall research questions, I will summarise my work as illustrated in Figure 7.

In Paper 1, we discerned the laboratory learning outcomes for students in five distinct clusters. In my model for laboratory learning, in figure 7, these clusters are in the outer ring. Inside the circle, I have placed the different factors shaping students’ experience of their learning, described in Papers 2 and 3. Indeed, there are more factors affecting students’ learning experiences – but these are the ones I have found to be central in my empirical data and work. In the middle is a grey circle representing what I have come to see as the central outcome of laboratory learning: That students get an understanding of the relationship between the “real” and the “ideal” through variation and transformations – this central learning outcome is unique to laboratory experiences and is considered in both Papers 3 and 4. I think that experiencing the transformations in the laboratory described in Paper 3 is significant for students irrespective of which conceptions of the theory-practice relation they hold.

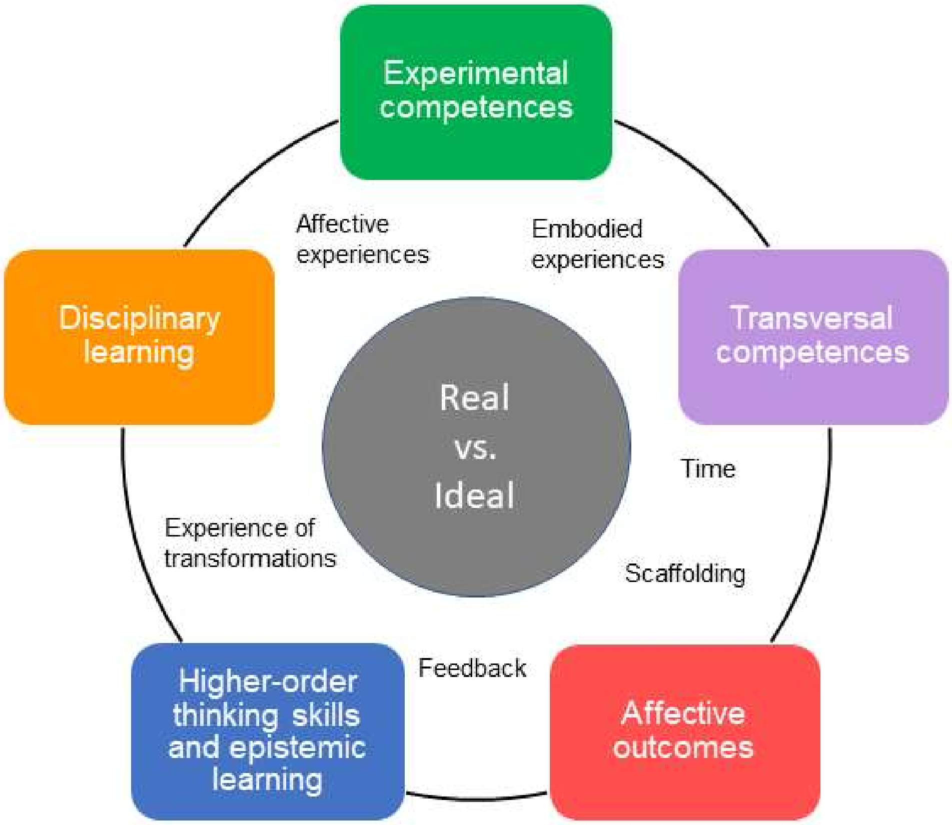

Figure 7: Model representing central findings from my thesis about laboratory learning, and encompasses all research questions. The middle represents the essence of laboratory learning: to understand the relationship between material objects in the lab (instruments, samples, setup etc.), and the ideal representations of them in protocols and theory. In the circle are described central factors influencing students' experiences of laboratory learning. Lastly the five boxes show the five clusters of student outcomes from laboratory work.

A crucial aspect emphasised in the literature (Tsingos et al., 2015; Wheeler, Maeng, & Whitworth, 2017; Wheeler, Maeng, Chiu, et al., 2017) and by the students in Paper 3 is the central role of the teacher and/or teaching assistants in the laboratory. The students explicitly mention that the discussions and feedback they receive during laboratory classes are of utmost importance for their understanding. When experiments are not giving the expected results, and students find themselves at a loss, the teachers play a crucial role. They provide vital feedback and support to the students toward understanding the interplay between our conceptions and the physical environment. The teachers show the students how to navigate and engage – to bridge the gap between the real and the ideal.

Engaging in feedback and dialogue with the teacher during laboratory sessions serves as a valuable place for the students to reflect on their practical work. This is needed for the students to establish meaningful connections between theoretical concepts and their practical experiments in the laboratory (Galloway & Bretz, 2016). This reflective process is significant as it allows students to derive purpose and meaning from their laboratory experiences. Without such opportunities for reflection, there is a risk of students perceiving their time in the laboratory as a waste of time, as discussed in Paper 2.

In Paper 4, I describe conception C, where the students begin to express that the important learning experience in the laboratory is based on them noticing the differences and unexpected situations between how they imagined the experiment would look and how it looks. They start to recognise that having a manual describing what to do is no guarantee that you are able to perform the experiment. This is where the teachers and other students come into play and help scaffold students learning into success. Through dialogue, teachers guide the students to see what it takes to make the experiment work. It is through dialogue with the teachers and peers that students get the chance to vocalise their understanding of what is going on. As mentioned in Paper 3, this is important for the students' learning experience.

Particularly, laboratory settings that simulate real work situations are considered authentic experiences, profoundly influencing the experiences of pharmacy and chemistry students in the laboratory, as shown by research (Harsh et al., 2011; Noble et al., 2019). Understanding how theory and practice are intertwined and supplement each other is also represented in the understanding of the laboratory as text production. Usually, students would define a text as theory and instruments and chemicals as practice, but it is exactly how one thing is transformed into the other that is extremely important, as emerging from my interviews with the students in Paper 3.

In summary, I suggest that focusing on the relationship between the ideal and real (rather than theory and practice) has the potential to be a central focus in laboratory teaching and learning, which will highlight the variation and transformations of representations that laboratory work entails. In seeking to bridge the gap between the real and the ideal, students may obtain learning outcomes from all five clusters if their learning is appropriately scaffolded.

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Appendix 1 : Paper 1 – Learning outcomes of university chemistry teaching in laboratories: A systematic review of the empirical literature

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SYNTHESIS

Review of Education BERA

Learning outcomes of university chemistry teaching in laboratories: A systematic review of empirical literature

Hendra Y. Agustian[1] | **Laura Teinholt Finne**[2] | **Jonas Tarp Jørgensen**[1] | **Maja Ingerslev Pedersen**[1] | **Frederik Voetmann Christiansen**[1] | **Bente Gammelgaard**[2] | **Jan Alexis Nielsen**[1]

[1]Department of Science Education, Faculty of Science, University of Copenhagen, Copenhagen, Denmark

[2]Department of Pharmacy, Faculty of Health and Medical Sciences, University of Copenhagen, Copenhagen, Denmark

Correspondence
Hendra Y. Agustian, Department of Science Education, University of Copenhagen, Niels Bohr Bygningen, Universitetsparken 5, 2200 Copenhagen, Denmark.
Email: hendra.agustian@ind.ku.dk

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Abstract

Laboratory work has been a common element of science courses at university level for around two centuries, but its practice has been criticised by scholars in the field and related stakeholders. Mainly on a rationale of financial justification and educational efficacy, more evidence for learning has been called for. The aims of this systematic review were to characterise learning in the laboratory and substantiate learning outcomes associated with laboratory instructions in university chemistry. Analysis of 355 empirical studies revealed that students develop five clusters of laboratory-related competences pertaining to *experimental competences*, *disciplinary learning*, *higher-order thinking and epistemic learning*, *transversal competences* as well as *affective domain*. These competences were specified into related constructs measured in the studies. Synthesis of published studies led to a substantiated view on multidimensional learning in the laboratory and its implications for research, practice and theory are suggested. Representations of research areas that deserve appraisals and further investigations are also proposed. The video abstract for this article is available at https://video.ku.dk/secret/76185334/73665cb966315601404b793ffc234a77.

KEYWORDS
chemistry education, goals, higher education laboratory work, objectives and outcomes of laboratory instruction

Context and implications

Rationale for this study

To provide comprehensive evidence for learning outcomes associated with laboratory work.

Why the new findings matter

Our research synthesis substantiates a multidimensional view of laboratory learning. There is a large scope for empirical and theoretical development in this complex setting.

Implications for researchers and practitioners

Future research should be directed towards a more comprehensive and rigorous inquiry into student learning that considers a more holistic view. Focus on higher-order competences is needed. Practice wise, laboratory curricula should better accommodate students' learning progression throughout their higher education. Assessment and feedback practices should be revisited.

INTRODUCTION

Experimental work is an indispensable element of post-secondary science curricula. However, with the increasing enrolment in STEM (Science, Technology, Engineering and Mathematics) programmes, individual laboratory work that caters for hundreds of students a year has become a challenge in terms of viability, logistic and resource distribution. Consequently, most of the modern laboratory instruction is often verificatory (also referred to as traditional, expository, or loosely termed 'cookbook'), such that more students can fit in a rotation system comprising several prescribed experiments for them to conduct.

Two of the pioneering reviews of laboratory education are Hofstein and Lunetta (1982, 2003). While these reviews pertain to school science rather than higher education science, some of the basic distinctions and findings are relevant for and have informed the current review. Thus, Hofstein and Lunetta (1982) provide an operational definition of laboratory work, which is also employed in this review. It defines laboratory work as 'contrived learning experiences in which students interact with materials to observe phenomena' (p. 201).

Taken together, the two reviews by Hofstein and Lunetta demonstrate the unrealised potentials of school laboratory work with a widespread failure in turning learning goals of school laboratory instruction into actual learning outcomes for students. They argue that in order to realise the potentials of laboratory instruction, there is a continued need for the examination of goals, and how specific laboratory activities and assessment formats can be designed to support these (Hofstein & Lunetta, 2003, p. 46). The reviews also argue that past research has tended to focus on a narrow conceptualisation of skills, which limited the application of the findings.

In terms of teacher's implementation of the curriculum, they argue that research also failed to substantiate teacher-student interactions in the laboratory, and how these reflected the intended curricula. In the context of undergraduate science education, Bradforth et al. (2015) argue that excellent teachers do so by linking their pedagogy to their own research. Focusing on teachers' teaching practices may substantially contribute to their professional learning, by means of researcher-practitioner collaboration and reflective activities (Ping et al., 2018).

Some of the arguments from research mentioned above have led to curriculum reforms, aimed primarily at improving student learning, including learning in laboratory settings. For instance, in the United Kingdom, *Good Practical Science* was published in 2017, providing a framework for schools to develop science curricula around practical work (Gatsby Foundation, 2017). One of the recommendations in the reform document states that the 'school should have laboratory facilities such that students can carry out extended practical science investigations' (p. 13). The reference to extended investigations can be interpreted as laboratory exercises that require a longer trajectory beyond a single period, presumably with a higher level of inquiry. However, students are yet to benefit from this type of laboratory work, as the report claims that many schools 'are not making full use of [the available laboratory facilities]' (p. 14). When they are, the extent to which students actually learn from laboratory work also needs to be substantiated.

A decade earlier, *America's Lab Report* presented similar findings (The National Academies of Sciences, 2006). At least in the context of school science education, their findings point to the lack of clarity in defining 'the laboratory' and 'laboratory work', which 'make[s] it difficult to reach precise conclusions on the best approaches to laboratory teaching and learning' (p. 2). Informed by research and curriculum reform recommendations, efforts have been made to improve learning in the laboratory by designing new curricula that reflect scientific inquiry, incorporate more investigative elements, authenticity, or some form of problem orientation.

As mentioned, Hofstein and Lunetta's reviews were concerned with school science education. An important article by Reid and Shah (2007) reviews some key studies of university chemistry education, but there is no systematic review of learning in the university teaching laboratories.

In higher science education, especially in physical science courses like chemistry, laboratory work occupies significantly more space in the curriculum, which can amount up to 400 h in an entire undergraduate chemistry degree (American Chemical Society, 2015). Accordingly, the role of laboratory in university chemistry is more structurally integrated within the curriculum (Reid & Shah, 2007). This prominence may indicate higher importance, but scholars have been very critical about assumptions and taken-for-granted practices associated with experimental work in university science (Buck et al., 2008; Hodson, 2005; Reid & Shah, 2007). Recent editorials on learning in the laboratory by Bretz (2019) and Seery (2020) point to the same concern from which we embarked on this major review. Both editorials assert the importance of providing comprehensive evidence for learning in the laboratory, particularly in its pivotal function as a place to do science. While their call for substantiation of learning may be read as a call for additional primary studies, we argue that a major secondary study will provide a timely overview of knowledge about learning from laboratory work. In the decades after the Hofstein and Lunetta (2003) review, digital technology has become pervasive in teaching laboratories both in measurement, data collection and interpretation. Virtual laboratories and simulations are becoming increasingly sophisticated and are used in conjunction with laboratory activities or, occasionally, replacing the laboratory activities altogether. Thus, as Hofstein and Lunetta argue for school laboratory instruction, Bretz and Seery argue for higher chemistry education: There is a strong need for research on goals of laboratory work and evidence of how teaching and learning activities can support student outcomes.

The present review aims to shed light on what empirical research has to say about evidence for learning in the laboratory. We focus on learning outcomes, representing the attained level of curriculum representations (Thijs & van den Akker, 2009). In doing so, we strive to consider coherence between *the intended* (learning goals, perceived roles of laboratory work), *the implemented* (laboratory instructions, pedagogical approaches), and *the attained* curriculum (learning outcomes, assessment results). In the discourse of curriculum development, coherence between these levels is considered paramount to successful teaching and learning (Porter et al., 2011; Voogt & Roblin, 2012), by ensuring that learning goals in the laboratory curricula are translated into appropriate pedagogies in the laboratory, including pre- and post-laboratory activities (Buck et al., 2008). But also, assessment of student learning should reflect the formulation of learning goals and mirror feedback practices in the laboratory. Our focus on learning outcomes is an attempt to trace this coherence back into the learning goals in university laboratories, as published in previous works (Buck et al., 2008; Mack & Towns, 2016), and in response to the aforementioned Bretz and Seery's editorials.

Unlike previous works, the present review also attempts to provide a comprehensive mapping, by incorporating a systematic review methodology. Essentially, we seek to address the following questions:

- How can learning in the laboratory be described and characterised?
- What are the learning outcomes associated with laboratory instruction at university level?

METHODS

Identification: search methods

Two electronic databases—ERIC and Web of Science—were searched using topical keyword searches of entire publications. The combination of ERIC and Web of Science allowed for a comprehensive coverage of peer reviewed English literature on the overall topic of our study. ERIC is widely recognised as the largest full-text database of education-related literature.[1] One possible drawback to use ERIC is the automated nature of ERIC's indexing. This can be offset with the parallel use of a person-curated database such as Web of Science. Deciding not to include more databases of course carries some limitations. Furthermore, other databases may for example catalogue non-English literature, however, it was not feasible for us to cover non-English literature systematically in this study. Other databases may catalogue more general literature that would not be indexed as educational—for example, studies of how persons behave in psychology laboratory research settings. But we were from the beginning focused on the learning potential for students in the educational setting of laboratories.

Search terms and search logic was selected to define essential elements of the object of the review aim. The search string for the Web of Science database search was: (TS = (laboratory OR lab OR laboratories OR “practical work” OR “experimental work”) AND TS = (teacher OR student OR education OR learning OR learn OR teach OR teaching)) *AND* LANGUAGE: (English) *AND* DOCUMENT TYPES: (Article OR Book OR Book Chapter) Timespan: All years. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC. The search string for the ERIC database search was: (laboratory OR lab OR laboratories OR "practical work" OR "experimental work") AND (teacher OR student OR learning OR learn OR teach OR teaching).

Screening: inclusion and exclusion criteria

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow chart of search and screening process for systematic reviews (Moher et al., 2009) acted as a guide for the current study. PRISMA provides an evidence-based minimal list of aspects to report in systematic reviews. Following PRISMA in no way ensures high fidelity, validity and reliability of a study; but as any widely accepted procedure, it makes it easier for readers to audit the decisions made in the review process.

The exclusion and inclusion of publications was a part of the so-called *screening phase* in the PRISMA statement (Moher et al., 2009)—that is, based on screening titles and abstracts. After these steps, in the *eligibility phase*, full-text readings were the basis for quality assessment. Publications were included if they were English language educational peer-reviewed research publications within the STEM disciplines that employed empirical studies to report on student learning outcomes related to chemistry education at the post-secondary level. Only journal papers and book chapters that were peer reviewed and written in English were included. This was instructed in the database searches, and so not a part of the screening per se. As stated above, it was not feasible to cover non-English literature systematically in this review. It is a limitation only to focus on English literature, but we do think that our vast scope in terms of time and area may offset some of the blind spots resulting in the narrow language coverage. Similarly, only focusing on book chapters and journal papers omits the substantial amount of 'grey literature' such as conference papers, white papers, government reports and so on. It was important for us to focus only on peer reviewed material to ensure a minimal compliance with research reporting criteria.

While the current review is particularly concerned with chemistry teaching in the university laboratory, we opted to include educational research within the STEM teaching gamut because it was hypothesised that a range of laboratory activities could be contextualised in the teaching of several STEM disciplines. Therefore, the term 'chemistry' was not a part of the database search. This strategy allows the authors at a later stage also to consider a comparative review of educational literature on laboratory learning within the different STEM disciplines. This decision is discussed below. Some inclusion criteria had to be refined iteratively within the group of coders who excluded and included publications. In the case of all but one of the inclusion criteria, we calculated the interrater reliability among the individual coders on a subset of the publications. The eventual list of inclusion criteria is presented in Figure 1, while the exclusion criteria are described with the inclusion criteria description in the following.

Regarding *inclusion criterion 1*, we required that the publications had to be on a topic within education research. This meant excluding titles such as 'Electrocardiographic and blood pressure effects of the ephedra-containing TrimSpa thermogenic herbal compound in healthy volunteers' (Caron et al., 2006), while retaining titles such as 'Electrocardiogram interpretation training and competence assessment in emergency medicine residency programs' (Pines et al., 2004). The coders only excluded a publication if they could rule out that the publication reported on a topic within education research. If the publication was published in an educational research journal, the coders automatically included it in the criterion, even if the title did not suggest it was concerned with educational research (e.g., 'History of hepatic bile formation: Old problems, new approaches' [Javitt, 2014]).

Regarding *inclusion criterion 2*, only publications on a topic within the field of STEM education were retained. This excluded titles such as 'A journey towards self-directed

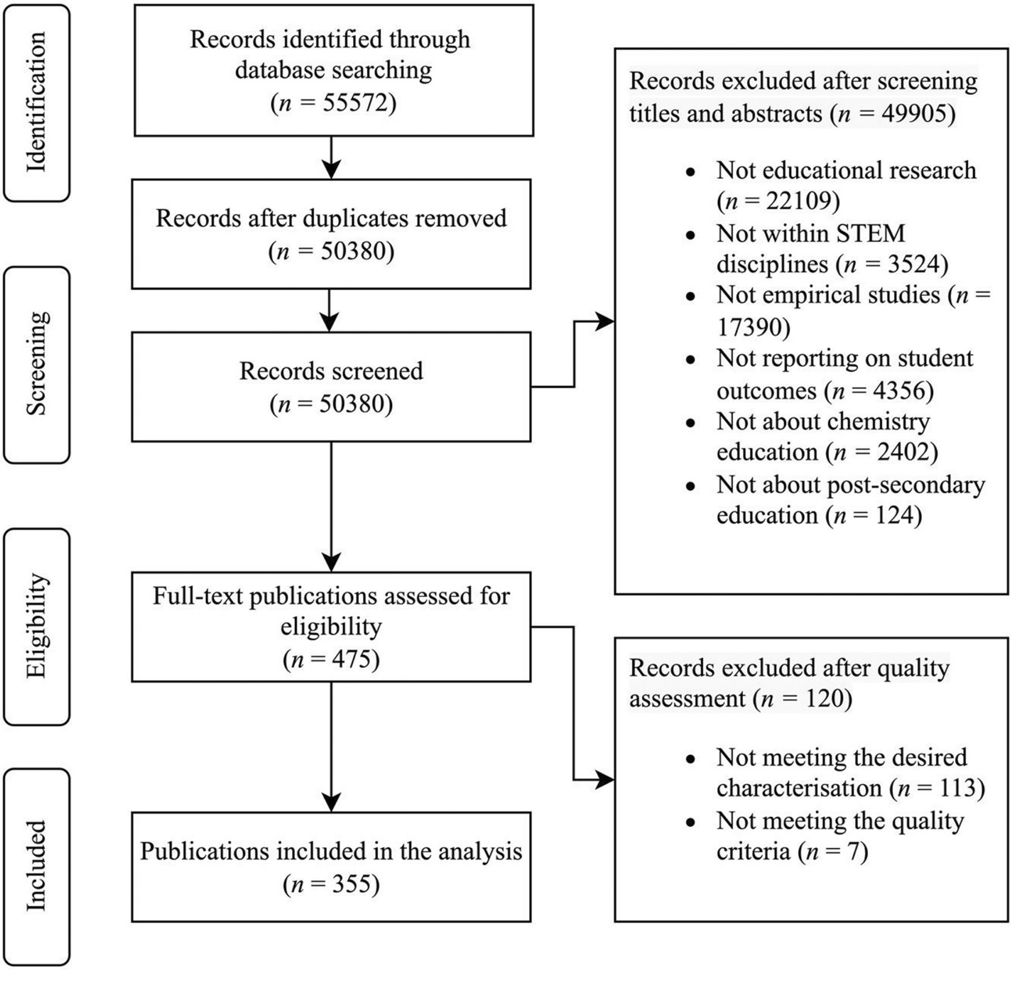

FIGURE 1 PRISMA (preferred reporting items for systematic reviews and meta-analyses) flow diagram of the search and screening process (including exclusion criteria) for the current systematic review (cf. Moher et al., 2009)

writing: A longitudinal study of undergraduate language students writing' (Olivier, 2016). The coders used a wide understanding of what constitutes STEM. Publications concerning areas of a more biological or chemical nature would be included, whereas publications concerning other areas of health care were excluded (e.g., 'The use of peer leadership to teach fundamental nursing skills' [Bensfield et al., 2008]).

Regarding *inclusion criterion 3*, only publications that reported on an empirical study were retained. Thus, literature reviews as well as course descriptions and descriptions of laboratory activities without collection of evaluative data were excluded. This excluded otherwise interesting publications that have informed our work in other ways (e.g., 'The role of laboratory in university chemistry' [Reid & Shah, 2007]). It also excluded detailed descriptions of well-made laboratory activities with little to no mention of empirical assessment, such as 'Peptide mass fingerprinting of egg white proteins' (Alty & LaRiviera, 2016). Course evaluations is a widespread tool for assessment of teaching and learning. In this criterion, articles were excluded if the course evaluation appeared to be the only assessment or data-point and if it appeared to constitute a minor part of the articles (e.g., 'Community-based presentations in the unit OPS laboratory' [Mitchell & Law, 2005]). This is not to say that course evaluations were discounted as empirical data, and articles where it appeared to have a more prominent role were included (e.g., 'Showing the true face of chemistry in a service-learning outreach course' [LaRiviere et al., 2007]).

Regarding *inclusion criterion 4*, only publications that focused on student outcomes were retained. This meant excluding studies that focused, for example, only on teachers/educators. We required that the publication included an investigation of the student outcome, and that this investigation was a primary focal point in the publication. Student outcome was taken to be all cognitive, affective, psychomotor, and epistemic proxies for learning. In order to operationalise this criterion, we aimed to include publications that had a stated aim or a research question about student outcome. But in order to gauge this from the abstract and title we used as a proxy the following coding criterion: In the abstract, the description of the empirical study of the student outcome gives reason for the coder to assume that the publication contains (i) a research question about student outcome, (ii) a sufficient description of research methods and (iii) an appropriate and coherent description of data analysis, regarding student outcome.

Regarding *inclusion criterion 5*, only publications that reported on studies that were explicitly about chemistry education were retained. This was done by searching for "chem" in the worksheet, excluding records that did not contain this element. Thus, the remaining publications containing "biochemistry" were included, but not "schema". Regarding *inclusion criterion 6*, only publications that reported on studies about post-secondary education were retained, excluding papers such as 'Secondary school students' attitudes to practical work in biology, chemistry and physics in England' (Sharpe & Abrahams, 2020), but including papers like 'Helping students understand formal chemical concepts' (Ward & Herron, 1980). We do believe that research on secondary level can inform the didactics and pedagogies in higher education, but we wanted to narrow our focus in this paper.

While it may seem ineffective to first code for the criterion about STEM-education (inclusion criterion 2) and then later code for the criterion about chemistry education (inclusion criterion 5), we wanted to keep open the possibility that we at a later stage can make a comparative review of educational literature on laboratory learning within the different STEM disciplines. Had we included 'chemistry' at the level of database search, we would have to retrace our screening steps up to this step in order to make comparisons between the findings on chemistry education and, for instance, physics education. Each screening step is labour intensive, so not having to retrace steps is preferable.

Eligibility: study selection

Publications identified through the Web of Science database search were exported as BibTeX entries and combined in a *.bib file. Publications identified through the ERIC database search were exported as PubMed nbib entries and imported as entries into an EndNote X9 library using the PubMed (NLM) filter; then the library was exported as a *.bib file. The two *.bib files containing all entries were converted into *.csv files using JabRef version 4 and were made to have uniform column titles and then subsequently combined in Excel version 16. Each entry was given a unique identifier on the format AXXXXXX. Many entries stemming from the ERIC database, were not retained in this process. Therefore a python script was made which retrieved the missing abstracts on the basis of the ERIC Accession Numbers of the publications.

This information (Accession Number and Abstract) was saved in a spreadsheet file and the data were imported into the master *.xlsx file containing all publications using Excel's VLOOKUP function using the Accession Number as the lookup value. Duplicate entries in master *.xlsx file were identified; first by using the conditional formatting in Excel to highlight cells (containing the title of a publication) with duplicate values; second, additional duplicates were found manually by going through entries with titles that contain special characters (these titles were often not found through the conditional formatting); third, in a few cases duplicate entries were identified in the screening phase.

For inclusion criteria 1–4 and 6, the exclusion procedure in the screening phase consisted of stepwise iterations of coding attempts with interrater reliability checks. In all cases, the process was as follows: (1) The group of coders discussed how a given criteria could be operationalised; this included discussing examples and finalising the formulation of the inclusion criteria. (2) Then the coders independently coded the same subset of randomly selected publications according to the criteria. (3) After all coders finished their coding, the data were compiled in Excel and interrater reliability score (Fleiss's kappa) was calculated. (4a) If the interrater reliability score was at least moderate (i.e., Fleiss's kappa above 0.41 (Altman, 1990), all publications to be coded in this step (including those used for interrater reliability analysis) were randomly and evenly distributed among the coders. (4b) If the interrater reliability was not satisfactory, the procedure restarted at point (1) above with the change in iteration that examples of disagreements in coding were discussed. Inclusion criterion 5 (explicitly chemistry education) was so closely tied to data in the database entries that no interrater reliability tests were needed. The interrater reliability scores for inclusion criteria 1–4 and 6 are presented in Table 1.

Inclusion criteria 4 and 6 were coded in *Abstrackr* (Wallace et al., 2012) using their machine learning tool, that sorted the articles as 'most likely to be relevant'. The coders preferred the tool, which had good search functions to highlight in green colour words that were indicators for inclusion, such as 'Student outcome', 'Students', 'Undergrad', and highlight in red colour words that were indicators for exclusion such as 'K-12' or 'high school'. At the end of the coding process, 1663 publications previously undecided because of doubts about whether to include or exclude were coded in a similar process to the main process. At the end of this screening process 475 publications remained.

Eligibility and assessment

Referring to the flowchart of systematic review as recommended by PRISMA (see Figure 1), the selected studies were subsequently evaluated in a two-step procedure. The first step of this procedure was characterisation of each study according to the following elements:

a. aims of the study, as formulated by the authors;
b. theoretical or pedagogical frameworks, which may refer to theories underlying the conceptualisation of learning or pedagogical approaches used in the study;
c. overarching methodology that guides the investigation;
d. methods pertaining to the nature of data collection (quantitative, qualitative or mixed methods) and the strategies thereof;

TABLE 1 Interrater reliability scores for inclusion criteria 1–4 and 6

Inclusion criteria	n_{coders}	n_{papers}	κ	95% CI	*p*
1. Including only educational research	3	101	0.65	[0.53, 0.76]	<0.0001
2. Including only studies concerning science, technology, engineering and/or mathematics education	3	197	0.95	[0.87, 1.00]	<0.0001
3. Including only empirical studies	3	268	0.79	[0.72, 0.86]	<0.0001
4. Including only studies with focus on student outcomes	4	100	0.60	[0.49, 0.72]	<0.0001
5. Including only studies related to post-secondary education	3	29	0.88	[0.67, 0.1.00]	<0.0001

e. research instruments to collect data, with some specification whenever available;
f. number of participants, with some specifications if there are control and treatment groups;
g. intervention, if available, with a brief specification; and
h. results, as a list of main findings, including negative findings if reported by the authors.

Thorough discussions between the reviewers consolidated the interpretation of the elements and corresponding findings, in order to warrant reliability. During this characterisation, several studies were excluded as they did not fulfil the inclusion criteria in the screening process—for example, the study was not conducted at post-secondary level, not related to chemistry laboratory, not pertaining to student learning outcomes, not an empirical study, and there was no access to the full text. The exclusion of these studies brought the number of selected articles down to 362.

The second step of the procedure was critical appraisal of the quality of each study in which the following aspects were considered (Alderson, 2016; Zawacki-Richter et al., 2020):

- quality of the study design
- quality of the results of the study
- relevance and applicability in the context of our review questions.

The main purpose of this step was to identify the most important studies and interesting findings for our following analysis. In this procedure, each aspect was rated on a scale from 1 to 3, whereby 3 was the highest rate. The quality assessment of the study design (elements a–g in the list above) was based on proxies such as a formulation of research questions or hypotheses as well as an explicit theoretical/pedagogical framework. It was also specified whether the methodology and methods were appropriate to address the aims of the study. This information could also indicate to what extent the study was conducted in a rigorous fashion. The following questions guided our analysis for quantitative studies: Is the sampling representative of the population? Is there a control group? Is the intervention relevant to the aims? For qualitative studies, the guiding questions were: Are the instruments appropriate to address the aims? Are the numbers of participants observed/interviewed adequate?

To address the quality of the results of the studies, we focused on the aims and results of the study and if the results were triangulated to support the claims made by the authors. But most importantly, we were particularly interested in the competences related to learning in the laboratory that could be identified from the study. We were looking for constructs related to learning that were explicitly mentioned by the authors, such as problem solving, critical thinking, understanding of the nature of science, and the like. We use the term 'competence' instead of 'competency' on a rationale that the nuanced difference in defining both terms from a research perspective points to the former being more specific in scope than the latter, contrary to a generalist perspective, as argued elsewhere (Agustian, 2022).

Lastly, we assessed the extent to which each study was relevant for our research questions on the laboratory-related competences and the extent to which the findings were applicable to other contexts, such as pre-university science context or other science disciplines that may offer laboratory courses. At the end of the second part of the critical appraisal, 355 studies remained for subsequent analysis and synthesis.

Data extraction and analysis

The remaining studies were coded with a focus on key competences related to laboratory instructions. In cases where authors did not report their findings in terms of competences or complex skills, we also looked at all proxies of student learning outcomes, including constructs pertaining to the affective or conative domains.

To capture every substantiated outcome, an inductive, bottom-up approach was applied. This process resulted in 424 descriptors ranging from ‘analytical skills’ to ‘environmental literacy’. These were combined, restructured and recombined in several steps to become 117 descriptors, 85 descriptors and eventually 32 codes, ranging from ‘experimental design’ to ‘understanding of the nature of science’.

Using these new 32 codes, all publications were coded by looking primarily at the results sections. Whenever necessary, other sections such as discussion and methods sections were also consulted for clarification. This process led to five large themes, experimental competences, disciplinary learning, higher-order thinking skills and epistemic learning, transversal competences, and affective outcomes. Each theme was associated with more than 100 articles, with overlaps between them. Multiple themes could be present in a single publication if it reported more than one aspect of student learning.

The writing of the entire analysis was based on the 32 codes and key information from the critical appraisal (quality and relevance). Corresponding full texts were continually consulted for clarification and specification. During the writing process and the analysis, the codes were reduced to 22.

RESULTS

Summary of included studies

The aggregate of included studies in our systematic review covers publications from 1972 to 2019, as shown in Figure 2. The oldest record is Uricheck (1972), on using interaction analysis as a tool to identify patterns of laboratory instruction which differentiate effective and ineffective teaching. The study demonstrates that students learn most when they are allowed some freedom to discover and clarify the learning goals for themselves. As such, they grow independent of the teacher, by developing the habit of thinking through a problem on their own initiative. Five decades have elapsed since this early work and some of the issues investigated are still relevant. As Figure 2 indicates, 2016 was the year with most publications with 49 studies identified. These cover topics as, for instance, assessment of authentic research experience (Evans et al., 2016; Harsh, 2016) or investigation into the role of physical environment in the learning process from a perspective of basic psychological needs (Sjöblom et al., 2016). Several published studies from this year also provide evidence for the positive impact of inquiry laboratory on student learning (e.g., Brown, 2016; Goodey & Talgar, 2016; Ural, 2016).

The included studies were published in a wide range of journals (Figure 3), from subject-specific journals in chemistry education such as *Chemistry Education Research and Practice* and *Biochemistry and Molecular Biology Education* to those with broader scope in science and engineering such as *International Journal of Science Education* and *Journal of Research in Science Teaching*. In terms of frequency, *Journal of Chemical Education* is by far the most popular medium with 105 publications, followed by *Chemistry Education Research and Practice* with 50 publications.

A large group of studies (more than 70) were conducted as an evaluation study of a laboratory course or an intervention. Around 50 studies described measurements of the difference in students’ learning outcomes between participating students and a control group. It is also noteworthy that qualitative research methods such as phenomenology, ethnography, and grounded theory are also represented. The majority of studies were quantitative,

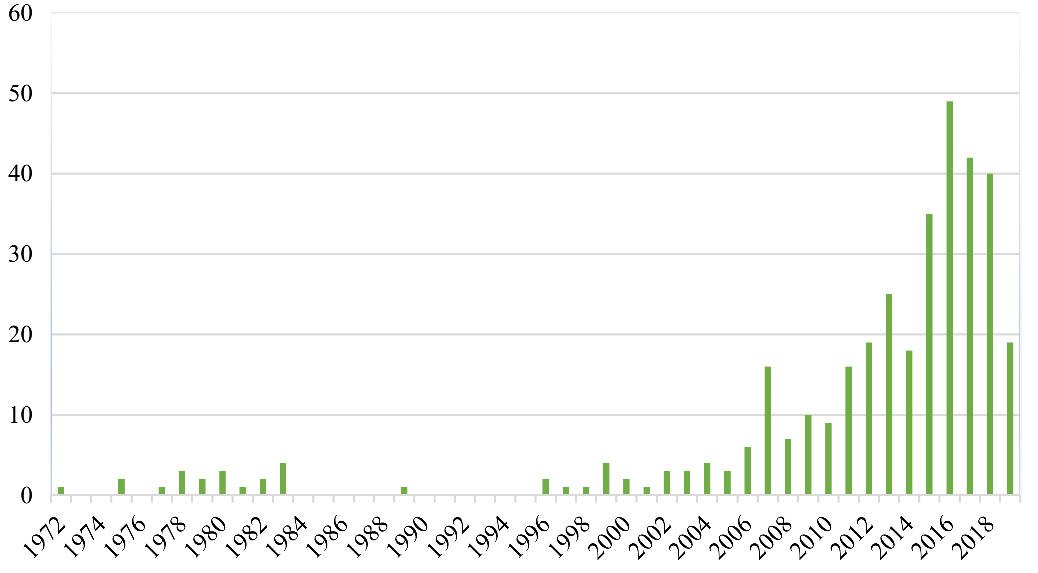

FIGURE 2 Number of publications per year

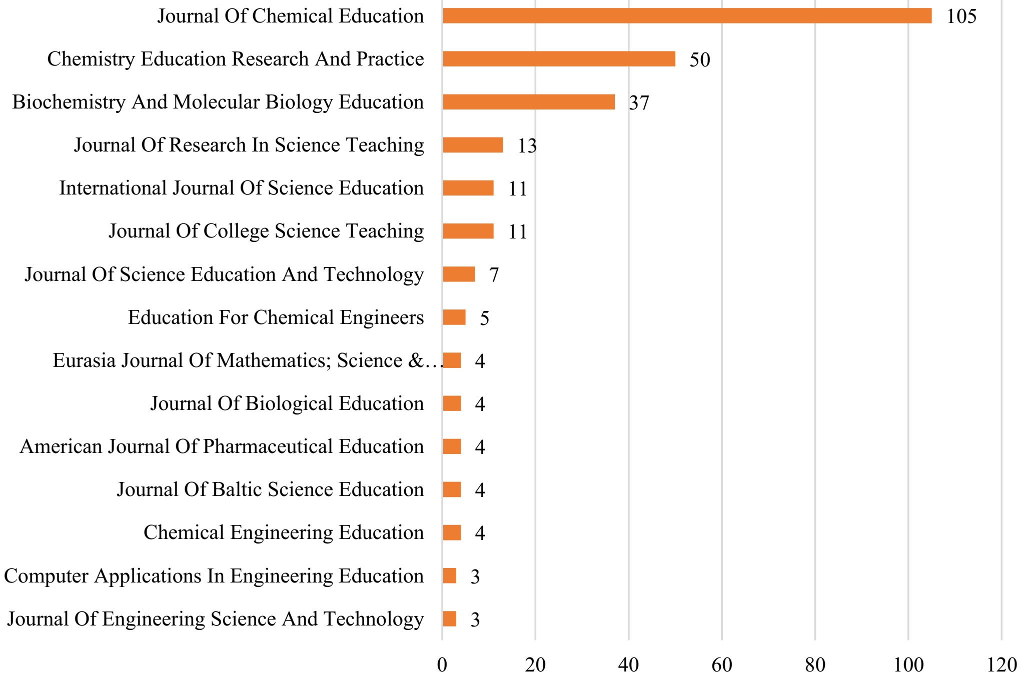

FIGURE 3 Frequency of publications (3 and more) in science education journals

as shown in Figure 4, mostly using questionnaires to collect data. As a whole, more than 110,000 students participated in the 355 studies we have reviewed.

The characterisation of the empirical studies in our review demonstrates that about three-fourths (263 out of 355) of the published studies have been conducted with a theoretical and/or pedagogical framework in mind. The extent to which the framework is stated and elaborated varies, but these studies have fulfilled the basic requirements for educational research, as widely established in science (and in particular, chemistry) education research (Abell & Lederman, 2007; Bunce & Cole, 2008, 2014). It is beyond the scope of this review to specify whether the theories or pedagogical frameworks espoused are the best choice for the intended research focus, but at the present level of analysis, the majority of the studies meet the quality criteria, from a viewpoint of this particular characteristic. The remaining 92 articles could benefit from a theoretical/pedagogical framework, in order to ensure that other elements of inquiry are illuminated by the recent development in the corresponding area of scholarship. For instance, the framework can and should be used to formulate 'theory-based [research] questions' (Bunce, 2008).

On that note, explicit formulation of research questions was missing in 222 studies (62.5%). Although these studies were still conducted with aims in mind (and stated in the article), they may benefit from an appropriate and explicit formulation of research questions, as it will drive the overall study and determine the course of direction the entire investigation is set to take, as argued by Bunce and Cole in their work on chemistry education research methodology (Bunce & Cole, 2008, 2014). Interestingly, our data show that most of these studies (170 studies, or about 75%) were published in the last decade (since 2010 up to the end of the search process in 2019). This signifies a room for improvement in the framing of the research problems, which could benefit from a clearer positioning with regards to the extant literature. Accordingly, we have identified that 181 studies did not incorporate triangulation of measurements. For instance, Hall et al. (2018) use the Course-based Undergraduate Research Experience (CURE) survey as the sole instrument to measure learning outcomes of interdisciplinary, inquiry-based medicinal chemistry laboratory.

The synthesis of 355 empirical studies on student learning outcomes associated with laboratory instructions is summarised in Table 2. As mentioned previously, five distinctive clusters have been identified, namely experimental competences, disciplinary learning, higher-order thinking skills and epistemic learning, transversal competences, and affective outcomes. Each of these clusters were further specified into related constructs that are mostly operationalised as research parameters measured in the studies.

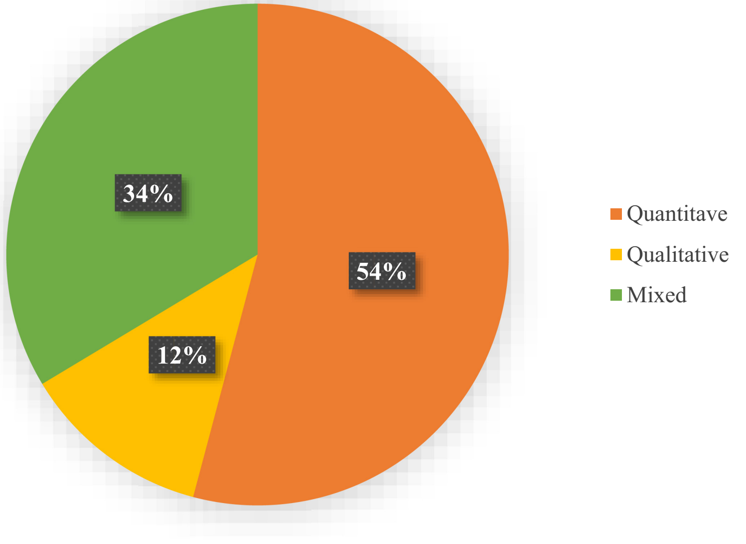

FIGURE 4 Data collection methods used in the studies

TABLE 2 Student learning outcomes associated with laboratory instructions

Clusters of learning outcomes	Substantiated constructs
Experimental competences	• Practical skills • Conducting experiments • Data analysis and interpretation • Experiment design
Disciplinary learning	• Conceptual understanding • Theory-practice connection • Academic achievement and mastery
Higher-order thinking skills and epistemic learning	• Problem solving • Critical thinking • Argumentation • Metacognition • Reasoning and reflection • Epistemic learning
Transversal competences	• Collaboration • Communication (oral and written)
Affective domain	• Expectations • Interest, enjoyment, and engagement • Self-efficacy • Laboratory anxiety • Motivation • Self-regulation • Professional identity

In the following sections, we will describe their key aims, interventions and results. Studies which are deemed highly relevant, rigorous, representable or interesting are described in greater detail and additional studies are referenced throughout to give a perspective on the depth and breadth of the corpus.

Experimental competences

In our review, 136 articles report student outcome with regards to the procedural process of the laboratory experiments, either by performing laboratory techniques, handling instruments, analysis and interpretation of data, or designing experiments. These constructs are synthesised and described as experimental competences, which we define as students' ability to plan, design and carry out a scientific inquiry efficiently and safely. Mastering this cluster of constructs requires that students understand the purpose of the investigation, are able to carry out relevant manipulative skills, analyse and interpret data, and understand criteria and arguments for evaluation of the quality of empirical data.

Practical skills

The act of doing chemistry and working in the laboratory is an important part of students' personal experience and development of their procedural knowledge of chemistry and experimental competences. Seung, Choi and Pestel (2016) examine 100 students' written argumentation for experimental procedures in laboratory reports from a process-oriented laboratory curriculum. In the process-oriented curriculum, experiments were progressing from training observation, over collecting data, synthesising findings, and employing technology to gain experimental claims. One of their major findings was that students' personal experience in practising chemical procedures helped the students to achieve epistemic knowledge.

The repetitive nature and ample room for practice in the laboratory are important for gaining valuable experiences and confidence in performing experimental work. This was demonstrated in a study of Warner et al. (2016) reporting that students' technical skills and perceived technical competences are correlated to their exposure to practical work in the laboratory. They surveyed the students' perceived technical competence (n = 876) compared to their exposure to instruments in the laboratory over 5 years and demonstrated that students scored themselves higher with more hands-on and direct exposure to the instruments. A similar increase in student's performance and confidence was reported by Erdmann and March (2014) when students were completing an assignment to make a video of performing a laboratory technique. The students (233 participating, 509 in total) increased their confidence and final grade significantly. Other examples of experimental design studies with control groups showing improvements in students' experimental skills have been reported (Gallion, Samide, & Wilson, 2015; Hass, 2000).

Of the 136 studies, 19 document that pre-laboratory activities such as videos, mental practice or synopses of the laboratory session improve students' practical skills (Box et al., 2017; Cavin & Lagowski, 1978; Jordan et al., 2016; Seery et al., 2019). For example, Beasley and Heikkinen (1983), compared practical preparation with mental preparation for experiments. In the experimental research study, students' performance (360 participants with 96 in control group) of specific practical skills as using the balance or a pipette were compared when one group practised the procedure in the laboratory, whereas another group practised mentally studying one of two pictorial illustrations with written instructions. The outcome was that practice helped the students perform the experimental tasks, regardless of whether it was the mental practice or the actual laboratory performance. In another study on pre-laboratory activities from 2001, Rollnick et al. performed an action research study with two iterations by changing pre-laboratory activity from questions to synopsis writing. Both studies are examples of the importance of engaging in meaningful pre-laboratory activities. Students' learning outcome is poorer when engaging in laboratory work without proper preparation, which is prevalent in our review findings (Box et al., 2017; Cavin & Lagowski, 1978; Darby-White, Wicker, & Diack, 2019; Jordan et al., 2016; Veiga et al., 2019).

Conducting experiments

Inquiry- or problem-based teaching approaches seem to be particularly effective in developing students' experimental skills. In our review, 48 of the 136 articles report pedagogical or theoretical frameworks that are problem-based or inquiry-driven. Essentially, these studies substantiate that inquiry-based laboratory activities increase the quality of students' experimental work. An example is a quasi-experimental design study by Goodey and Talgar (2016), where they compare inquiry-based laboratory exercises with a cookbook approach (103 students in total, 36 in treatment group) and report that students doing the inquiry-based experiments performed significantly better in the Experimental Design Ability Test. Furthermore, inquiry-based laboratories improved students' independence and experimental competences—for example, as reported by Silva and Galembeck (2017), that increasing autonomy in the laboratory exercises stimulated students' experimental planning skills; this was assessed through the quality of 180 students' laboratory reports. Likewise, the discourse in inquiry-based laboratory activities has been documented to change from mere expository guidance to procedural knowledge reflections. An example of this is a study by Xu and Talanquer (2013a, 2013b) who demonstrated that inquiry settings in the laboratory prompted students to pose ideas, test hypotheses, and explore more compared to non-inquiry settings through observation of 20 students. Similar findings were also reported by Krystyniak and Heikkinen (2007).

Awareness of safety in the laboratory is very crucial to student learning processes and outcomes. This may be associated with their psychomotor domain of learning (Flaherty et al., 2017), and we argue that this is a part of experimental competences. In our review, attention to safety issues as a part of learning outcomes has also been reported by, among others, Inguva et al. (2018) in their design and development of a chemical engineering course and Walters, Lawrence and Jalsa (2017), focusing on laboratory safety awareness. However, the latter found that although awareness among students of hazard identification, emergency response and waste disposal was high, they did not necessarily read safety documents. This was found to be a predictor of laboratory accidents, which suggests that safety awareness should be incorporated into laboratory curricula.

Authentic research experiences such as Course-based Undergraduate Research Experiences (CURE) or Undergraduate Research Experiences (URE) seem to positively influence the development of students' practical skills and experimental competence (Chase et al., 2017; Nadelson, Warner, & Brown, 2015; Williams & Reddish, 2018). In a large-scale mixed-methods study with 116 interviewees and 4285 survey respondents, Harsh et al. (2011) reported that students considered ‘exposure to genuine, authentic research experience’ most important (49%), followed by ‘building confidence to conduct research’ (16%), and ‘development of experimental skills’ (15%). Thus, it is evident from our review that such experiences increase students' understanding of the process of research and what scientists actually do. In another study on 33 students in a CURE setting, the outcome, based on a survey and interviews, was an improved understanding of the research process and readiness for future research (Williams & Reddish, 2018).

Data analysis and interpretation

Data analysis and interpretation are crucial in university science. In this regard, 26 articles report student outcomes of laboratory learning related to data-analysis and interpretation (Díaz-Vázquez et al., 2012; Hall et al., 2018; Iler et al., 2012; Johanson & Watt, 2015; Kappler, Rowland, & Pedwell, 2017; Kowalski, Hoops, & Johnson, 2016). Two studies demonstrate that an effective way of developing these skills is by allowing students to encounter real and raw data, instead of curated or computer-simulated data (Hill & Nicholson, 2017; Witherow & Carson, 2011).

Experiment design

An important part of being a scientist is the ability to design an experiment. Twenty-one studies in our review provide evidence that students learn some form of experiment design from the laboratory experiences (Alneyadi, Shah, & Ashraf, 2019; Cacciatore & Sevian, 2009; Turner, Jr. & Hoffman, 2018; Winkelmann et al., 2017). In a project-based learning setting, where students followed a year-long course, where they in groups explored a new, undescribed protein through five research phases, they improved their ability to design experiments (Li et al., 2019). Third-party assessment scores from 0–10 assessed the improvement and the involved students scored at least one point more compared to a control group at the same level not participating in the same learning setting.

The overall impression of the literature is that evidence for describing experimental design as a learning outcome of laboratory courses is not very strong. But at least five studies suggested a specific method, template or structure to scaffold the students’ understanding of experimental design that increased their designing skills (Anwar, Senam, & Laksono, 2018a; Arias, Lazo, & Cañas, 2014; Coleman, Lam, & Soowal, 2015; Goodey & Talgar, 2016; Willoughby, Logothetis, & Frey, 2016).

Disciplinary learning

More than 190 of the articles in this review focus on either conceptual understanding, theory-practice connection, academic achievement, or students' mastery of a discipline. These constructs include learning outcomes such as theoretical or curricular knowledge, understanding of the connection between the experiment and the underlying theory, higher grades or other improvement in assessment, and progression in their higher education. For this review, these articles are labelled as investigations on various aspects of *disciplinary learning*.

Conceptual understanding

Conceptual understanding in this context is defined as understanding the underlying accepted theories and methods in the experiment. Content-based assessment is the most common approach to measuring student learning in the laboratory, as reflected in research questions exploring the extent to which students ‘learned more’ as a result of an intervention. Those studies are often based on course evaluations, which is generally considered somewhat weaker evidence, but not without merit as it can be very close to the actual context, and in some cases, considerable rigour is applied in the evaluation. About a third of the reviewed studies mention conceptual understanding as a central student outcome from the laboratory work.

Implementations of a more open-ended, investigative and inquiry nature of laboratory experiences have shown to increase students' conceptual knowledge. For instance, Díaz-Vázquez et al. (2012) conducted an intervention study with 400 students by introducing interdisciplinary experiments and student-driven research projects. Students learned concepts better when the laboratory teaching was investigative, with peer-review and cooperative learning. Likewise, Iler et al. (2012) developed and implemented guided inquiry laboratories in a second semester general chemistry course with 50–60 students. In this setup, students were challenged to rediscover basic theoretical principles by looking for patterns in data and testing their own explanations. Their course evaluation showed that students improved their ability to explain and correct their own misconceptions. In another course evaluation study based on interviews and pre- and post-tests, Weinlander, Hall, and de Stasio (2010) assessed two open-ended laboratory investigations and concluded that students could learn abstract concepts when the teaching incorporates real-life applications.

The benefit of problem-based learning and inquiry-driven experiments in development of conceptual understanding is supported by the work of Domin (2007) who used questionnaires and interviews to compare the learning experiences of 17 students in problem-based learning and traditional expository approaches to laboratory experiments. The findings indicate that problem-based learning approaches led to students' conceptual development *during* the experiment, while the conceptual development that arose from the expository approach occurred *after* the experimental activities. From other studies, it appears that students' conceptual understanding *during* the laboratory activity can be supported through various scaffolding interventions such as concept reinforcement (Pierce & Pierce, 2007), the use of analogies (Avargil et al., 2015), problem-based learning (Günter et al., 2017), or guided-inquiry experiment demonstration sessions (McKee et al., 2007).

Kiste et al. (2017) investigated the implementation of four integrated lecture/laboratory (studio) classrooms for engineering students taking general chemistry. Students' work in these studios alternated between laboratory work, group discussions, problem solving, lectures, computer simulations and assessment. The study was theoretically and methodologically rigorous, investigating 684 students split in treatment and control groups. The data were triangulated by combining content knowledge in pre- and post-tests, learning attitude surveys and students' course evaluations. They found that students' content knowledge, measured at final exams, improved significantly compared to traditional teaching. Taken together, these studies tell us that interventions using active, open-ended, investigative, inquiry-based, or similar teaching can lead to an increase in conceptual understanding gained from a laboratory course.

Students' prior knowledge can determine the success of their preparation for a laboratory activity, as confirmed with an action research study by Rollnick et al. (2001) and with a detailed mixed-methods approach by Winberg and Berg (2007). Furthermore, by interviewing six students three times during a semester, Emenike, Danielson and Bretz (2011) documented that students' prior knowledge has effects on how they experience and narrate their conceptual learning.

A very important finding is that conceptual discussions should accompany laboratory work, for students to reflect and refine their conceptions. By observing and interviewing 13 students, Galloway and Bretz (2016) demonstrated that without explicit conceptual discussion activities, students may develop psychomotor skills, but not cognitive skills in the laboratory. The students they followed typically held off on conceptual reflections until writing of a report, and the first time students reflected on the conceptual parts of the laboratory activities was often in the research interview. These findings resonate with the experimental study of Saribas et al. (2013), which substantiates that including metacognition tasks in laboratory work (e.g., discussing design and implications of experiment) led to better conceptual understanding. Evidence based on the collection and analysis of 36 laboratory reports showed that higher levels of inquiry resulted in a higher proportion of metacognitive questions from students, but that there was no correlation between the level of inquiry and student reflection on chemical concepts (Xu & Talanquer, 2013a).

Some studies report on the use of IT for scaffolding conceptual learning. Koretsky et al. (2008) recommend virtual laboratories as complementary to physical laboratories, and interestingly found that a virtual laboratory may be more efficient for learning concepts than physical laboratories. This recommendation was based on development and implementation of a virtual laboratory, which they assessed in an experimental setup using a think-aloud data collection method with 119 students in 46 groups. However, this finding was only based on surveys at the end of the course. Others find no significant difference between the two types of learning settings (Carvalho-Knighton & Keen-Rocha, 2007; Dalgarno et al., 2009). Finally, one study showed that the use of interactive videos did not enable students to overcome higher-level conceptual difficulties (Granjo & Rasteiro, 2018).

Theory-practice connection

Understanding the practices and processes of laboratory work can lead to a better understanding of relevant concepts and theory (Seung et al., 2016). One of the most common justifications for laboratory teaching is the theory-practice connection, and more than 10 studies have focused on students' ability to connect theory to practice and the impact of different laboratory activities on this ability. Student appreciation of theory-practice connection was confirmed by Borrmann (2008) who showed that students appreciated linkages between theory and observations and valued laboratory education more if it is highly connected to theory from lectures. This study included more than 370 students and accounted for biases in student opinions. In two studies, authors developed local teaching practices, and both emphasise the link between theory and practice. Chaytor, Al Mughalaq and Butler (2017) found that use of pre-laboratory videos facilitated students' learning of the concepts presented in an experiment (gauged with post-laboratory surveys). Warner, Brown and Shadle (2016) reported that students acquire more knowledge of instrumentation, when they spend laboratory time producing their own data as opposed to merely learning indirectly about the data collection (gauged with surveys and test scores).

In contrast, there are examples of rigorous studies which report negative or neutral findings of the theory-practice connection, all because the primary foci of the students or the interventions were elsewhere. In one pre-test post-test control group study, a new learning situation was assessed inferior to the old one, and authors suspect that an upcoming exam interfered with their data collection (Liang & Gabel, 2005). In a large project converting all laboratory teaching in the entire study programme to context-based inquiry teaching, the researcher investigated the students' perceived skills development through a survey containing closed as well as open questions. The result was an increased focus on practical and transferable skills, but focus on theoretical understanding did not change (George-Williams, Ziebell, et al., 2018).

Academic achievement and mastery

More than 50 studies in our review investigated students' academic achievement by metrics as depicted in grades or scores in final exams, tests or quizzes. Academic achievement is of course tightly related to conceptual development, but in contrast to the studies reviewed in the previous section, the studies reviewed in this section predominantly foreground academic metrics about the attainment of intended learning outcomes more broadly and use changes in those metrics to make conclusions about the efficacy of specific approaches or conditions.

Grading is the simplest and most common instrument for measuring achievement, and students place high importance on grades as a measure of their achievements in laboratory course work. This was the result of a survey among students about their goals for laboratory work and thorough analysis of more than 600 responses (Santos-Díaz et al., 2019). Similar strong evidence for the importance of grades as an extrinsic motivational factor was found by Mazlo et al. (2002) in their experimental setup where students ($n = 400$) were better prepared for the laboratory activities when their pre-laboratory quiz scores affected their grades. The importance and the accessibility of grades led to many studies using grades and final exams as a measure of outcome, often in combination with other measures (Ferrer-Vinent et al., 2015; Islim & Cagiltay, 2016; Small & Morton, 1983).

Various interventions have been found to successfully improve students' academic achievement, such as guided inquiry (Akkuzu & Uyulgan, 2017; Ural, 2016), cooperative learning (Saleh, 2011), and context- and problem-based learning (Baran & Sozbilir, 2018). As additional examples, academic achievement improved in studies, where they exposed students to a variety of interventions, such as an authentic performance project (Wilson & Wilson, 2017), use of a laboratory manual that promotes visual information processing (Dechsri et al., 1997) and use of concept maps (Ghani et al., 2017). Also, an entirely redesigned course that combined contextual, collaborative and inquiry-based learning in the laboratory and sought to give students a sense of ownership of their education, had a positive impact on academic achievement (e.g., Pezzementi & Johnson, 2002).

It can be beneficial to develop laboratory teaching that includes both a physical and a virtual part. This may manifest in big setups with live and virtual laboratories (Goudsouzian et al., 2018; Johnston et al., 2014). Also, at least six studies show that multimedia, video or online interactive preparation resources can positively influence student performance (Chaytor et al., 2017; Nadelson et al., 2015; Stieff et al., 2018; Veiga et al., 2019; Whittle & Bickerdike, 2015), which corresponds well with the finding that delegating some work from post-laboratory to pre-laboratory can improve performance at the final exam (Pogačnik & Cigić, 2006). In this study, the authors changed a course, conducted questionnaires, interviews, observations and collected exam scores from more than 200 students pre- and post-intervention. Another important finding is that laboratory teaching in combination with lectures leads to better academic achievement compared to lectures alone, as found by Matz et al. (2012) and Rowe et al. (2018) when 386 students responded to their survey about courses with or without laboratory components.

So far, we have focused on the evidence in the literature on students' content learning. In addition to content learning and performance (as reflected in grades and scores), at least 19 studies investigate more complex types of disciplinary learning. An overarching interpretation of these studies as a body of research is how students develop as they get closer to mastering a discipline.

For students to master the discipline of scientific laboratory work, Dillner et al. (2011) restructured their laboratory curriculum into integrated laboratories, rather than division in traditional chemical sub-disciplines and found through course evaluations and focus group interviews, that integration facilitated students' ability to work on research-like projects. When Harsh (2016) developed the instrument Performance Assessment of Undergraduate Research Experiences (PURE), it was found that mastering a discipline entails that students develop both laboratory skills and scientific thinking skills. Similarly, Szteinberg and Weaver (2013) introduced research experiences early in the laboratory course and found that mastering a discipline entails improvement in an array of learning outcomes. They did a three-year longitudinal study where they surveyed more than 500 students and interviewed 23 students to track students' perception of laboratory courses.

When students do work that resembles the scientific process, with self-design, problem-solving and creativity, it strengthens their independence and growth as a scientist (Gao, 2015). In a large mixed-methods longitudinal study with 116 interviewed individuals and 4300 survey respondents, Harsh, Maltese and Tai (2011) found that exposure to Undergraduate Research Experiences (URE) was highly valued by students. This underscores the point that feeling competent in the laboratory and being able to work independently leads to a positive view of chemistry as concluded by Lyall (2010) after introducing independent work and a less organised environment in a course. We will return to these last examples also in the section on affective outcomes below.

Higher-order thinking skills and epistemic learning

The selected empirical research literature in our review demonstrates that university students learn higher-order thinking skills through laboratory work (Díaz-Vázquez et al., 2012; Krystyniak & Heikkinen, 2007; Oliver-Hoyo et al., 2004). One of these studies was dedicated to investigating the use of an inquiry-based laboratory to foster higher-order thinking skills in particular (Madhuri et al., 2012). Higher-order cognition refers to a host of critical, systemic, creative and evaluative cognitive processes that lend themselves to more complex tasks such as problem solving and critical thinking. The concept is often compared to lower-order cognition, which refers to manual or algorithmic manipulation of cognitive process such as memorisation and rote learning. In our review, the following constructs have been substantiated, namely problem solving, critical thinking, argumentation, metacognition, reasoning and reflection, and epistemic learning.

Problem solving

According to OECD (2004), problem-solving competence refers to students' capacities to identify a problem and its constraints, present possible alternatives to solution, select solution strategies to solve the problem, reflect on the solutions, and communicate the results. In our review, at least 14 studies found that laboratory exercise facilitates the acquisition of problem-solving competence (Amante et al., 2011; Hill et al., 2019; Li et al., 2019). Some of these findings also suggest an association between problem-solving competence acquisition with undergraduate research experience (Burt, 2017; Shadle et al., 2012) and problem-based laboratory curriculum (Gürses et al., 2007; Lanigan, 2008; Shultz & Zemke, 2019). Analyses of student responses to surveys and interviews from these studies indicate that problem-solving competence acquisition involves an integration of many types of knowledge and necessitates self-regulation of learning.

Evidence from research shows that certain types of laboratory curriculum and pedagogical approaches such as problem-based and industrially situated laboratories (Koretsky et al., 2011; Zoller & Pushkin, 2007) could help students think at higher cognitive levels by allowing them to work on authentic experimental tasks, even in a virtual setting. These studies provide recent evidence of the effect of problem-based laboratory instruction on student learning, in comparison to other non-laboratory instructional contexts such as lectures and classroom demonstrations. Accordingly, other studies conducted by Díaz-Vázquez et al. (2012) and Kaberman and Dori (2009) are particularly interesting, as they used longitudinal case studies and experimental design methodology involving more than 1000 students, with appropriate triangulation of data analysis and interpretation. They found that student learning outcomes pertaining to higher-order thinking skills also manifested as an increase in critical thinking, question posing of a more substantial and theoretical nature, and sense-making of 3D molecular models.

Critical thinking

Critical thinking has been lauded as one of the most important goals of higher education that can benefit students in their personal and professional life beyond university. Various attempts have been made to define critical thinking, among others, by categorising the construct into skills and disposition (Huber & Kuncel, 2016). Others, like Moon (2007), strive to synthesise how learners, teachers and laypersons perceive what it means. In our review, 15 studies have found that laboratory instruction led to critical thinking (Chase et al., 2017; Knutson et al., 2010; Vitek et al., 2014). Chase et al. (2017) examined 86 students taking a course-based authentic research experience and measured their critical thinking using the Critical-thinking Assessment Test (CAT). Although they used a small sample and the study lacked a control group, they found that students' critical thinking improved upon taking such a laboratory course. As a comparison, Vitek et al. (2014) developed a grading rubric to measure critical thinking of 11 students enrolled in clinical chemistry. They, too, reported learning gains in this higher-order cognitive skill. Both publications properly described limitations of their study. However, from a viewpoint of research synthesis, there is a lack of clear definition of what the construct 'critical thinking' means. In Chase et al.'s study above, they define the construct in terms of other constructs that we also synthesise in this review, that is, creative thinking, problem solving, data interpretation and analysis, and communication. In comparison, Stephenson and Sadler-McKnight (2016) define it as self-regulatory judgement that is based on evaluation of evidence, context and methodology. In most of the other that reported critical thinking as a learning outcome, the construct was not defined. Considering the widely popular use of the construct, it is relevant to clarify what it means in the context of laboratory teaching and learning.

In general, critical thinking in the laboratory was acquired through research experience at undergraduate (Chase et al., 2017) and doctoral level (Philip et al., 2015), team-based learning approach (Belanger, 2016; Carrasco et al., 2019), problem-based curriculum (Koretsky et al., 2011), and science writing heuristics (Stephenson & Sadler-McKnight, 2016). In their analyses, researchers often report this outcome along with acquisition of other competences such as problem solving, scientific reasoning, self-directed learning, as well as collaboration and communication skills. This mirrors the development of the conceptualisation of critical thinking in the literature.

Argumentation

As an educational construct pertaining to higher-order cognition, argumentation is central to science education, as reflected in curriculum reform documents and leading science education journals (Erduran et al., 2015; Osborne et al., 2016). It emphasises the evidence-based justification of knowledge claims and draws on a mix of content knowledge, procedural knowledge and epistemic knowledge. We have analysed at least eight studies that may provide evidence for learning related to argumentation in science (Kadayifci & Yalcin-Celik, 2016; Seung et al., 2016; Walker & Sampson, 2013). Of these, Walker's research group has been consistently producing empirical work of considerably high quality focusing on students' ability to use the core ideas presented in the laboratory to explain a phenomenon and solve a problem (Walker et al., 2016), students' difficulties with elements of argumentation (Walker et al., 2019), and students' development of argumentative competence (Walker & Sampson, 2013). One of the rather striking findings from their studies is that students do not seem to change their reasoning even when provided with contradictory evidence. It is also noteworthy that the empirical findings relating to the acquisition of argumentation competence may provide a support for inquiry-type experiments, as opposed to confirmatory experiments (Katchevich et al., 2013), as the discourse during such laboratory exercise has been found to be rich in arguments.

Metacognition

As a construct, higher-order thinking skills are closely related to metacognition, which belongs to an established corpus of research in its own. Metacognition refers to an awareness of one's own learning and thinking process. In their edited work 'Handbook of Metacognition in Education', Hacker et al. (2009) maintain that metacognition consists of basic components applicable to almost any learning tasks, including laboratory work. These basic metacognitive components are often described as constructs related to knowledge and beliefs about cognition, monitoring cognition and regulating cognition. In our reviews, at least seven studies make an explicit reference to metacognition in their analysis and findings, either as a focus of investigation (Mathabathe & Potgieter, 2017; Sandi-Urena et al., 2011) or as a part of learning assessment results emerging from the data (Teichert et al., 2017; Xu & Talanquer, 2013a). Some of these quantitative findings indicated that students increased their ability and metacognitive strategies in solving online ill-structured chemistry problems. Meanwhile, others succeeded in characterising metacognition in terms of regulation of learning and corresponding strategies. The fine-grained coding system developed by Mathabathe and Potgieter (2017) allowed for a theoretical elucidation of the social nature of metacognition at play in collaborative laboratory work. As with higher-order thinking skills, the substantiation of metacognitive learning outcomes in our review also resulted in other related outcomes, such as problem solving, modelling skills, and understanding the nature of science (Sandi-Urena et al., 2011, 2012; Saribas et al., 2013).

Reasoning and reflection

Reasoning and reflection are considered as important competences that transcend disciplinary boundaries, especially in educational contexts where self-regulated learning is required (Tillema, 2000). Likewise, both of these constructs have been around for centuries in philosophical writing, often manifesting in the notion of dual processes of thinking: one fast and intuitive, the other slow and reflective (Evans, 2019). In the context of laboratory education, researchers often refer to these terms in various degrees of analyses and conceptual elaboration. This is captured in at least 13 studies in our review (Coleman et al., 2015; Furlan, 2009; Xu & Talanquer, 2013a). The study conducted by Galloway and Bretz (2016) is particularly insightful as it inquired into the cognitive processing that took place while students were watching themselves in the video recording of their laboratory work. The retrospective interviews afforded them an opportunity to stop and think about the chemistry behind the experiment they did. Varying degrees of understanding were revealed and only a few students could explain the purpose of the steps they carried out, albeit laden with inaccurate chemical ideas. Accordingly, another study by Gopal et al. (2004) also shows how reflection on laboratory work allows students to identify and change misconceptions so they can further refine their conceptions. The acquisition of reasoning and reflective competences through laboratory exercise can seemingly be facilitated with writing tasks that go beyond standard laboratory report formats. Interventions using reflective writing (Han et al., 2014) have been shown to be effective in helping students develop scientific reasoning and reflection skills.

Epistemic learning

Apart from learning outcomes in higher-order cognition, the studies in our review also provide evidence for epistemic learning—that is, learning how knowledge is established with respect to the material world, and how it is structured, produced and justified. Although closely related, this domain of learning is distinct from the cognitive domain in a way that it shifts the focus from *the learner*—along with their cognitive apparatus and associated processes—to *the learned*, that is, the nature, origin, limit and justification of the target knowledge. It also looks into the entire process that generates such knowledge.

In their study on the effect of cooperative problem-based chemistry laboratory instruction on graduate teaching assistants' epistemological and metacognitive development, Sandi-Urena et al. (2011), found that students were afforded opportunities to reflect on some important epistemological aspects of laboratory work and the knowledge it purports to generate. But most prominently, laboratory work has been found to facilitate an understanding of the nature of science (Marchlewicz & Wink, 2011; Pagano et al., 2018; Russell & Weaver, 2011). The terminology 'nature of science' typically refers to the epistemological commitments underlying the activities of science, that is, science as a way of knowing, or the values and beliefs inherent to the development of scientific knowledge (Bell et al., 2000). It also entails an understanding and appreciation of the work of scientists, processes of science and sociology of science (Yacoubian & BouJaoude, 2010). As a concept, it has been in a discourse of science education for well over a century. Eleven studies have substantiated these learning outcomes through various pedagogical approaches and theoretical frameworks, including research-based laboratory pedagogy (Russell & Weaver, 2011), process-oriented laboratory curriculum (Seung et al., 2016), constructivism (Cessna et al., 2009), activity model of inquiry (Marchlewicz & Wink, 2011), and meaningful learning (Saribas et al., 2013).

The empirical studies leading to substantiation of students' understanding of the nature of science in the context of the laboratory provide us with relevant insight into the role of the laboratory in fostering epistemic learning. Considering the current theories on the conceptualisation of this construct in science education (Allchin, 2013; Erduran & Dagher, 2014; Lederman, 2006), it is relevant to specify which theoretical frameworks the authors in our review have used. Four studies with explicit conceptualisation of the nature of science seem to refer to the consensus approach, which was initially proposed by Lederman's research group at the beginning of the twenty-first century (Akkuzu & Uyulgan, 2017; Marchlewicz & Wink, 2011; Russell & Weaver, 2011; Saribas et al., 2013), whereas the remaining seven in our review did not make an explicit reference to any theory on the nature of science. This is relevant to guide future research in laboratory education that wishes to focus on the epistemic domain, as the contemporary approach tends to highlight epistemic practice and family resemblance, as opposed to an attempt to find a consensus between various science disciplines.

Transversal competences

Apart from discipline-specific knowledge and skills, laboratory work has also been found to facilitate the acquisition of transversal competences. The construct ‘transversal competences’ has gradually gained recognition as one of the desirable outcomes of higher education, particularly in professional and vocational education, but has been somewhat neglected in competence research (Mulder, 2017). Authors in our review also refer to them as generic skills (George-Williams et al., 2018; Shultz & Zemke, 2019; Ynalvez, Ynalvez, & Ramírez, 2017). Although there is no consensus on what those constructs exactly mean, it is generally agreed that they are fundamental for a learner in applying knowledge, skills and attitude to meet an increasingly complex societal and professional demand. Some of the proxies of characteristics of transversal competences include transferability and cross-functionality, and thus, the constructs pertaining to higher-order cognition above are also transversal. In our review, it is sometimes signified with the term interdisciplinarity (Mulligan et al., 2011; Richter-Egger et al., 2010). Transversal competences are also typically related to social and interpersonal relations. The transversal competences have been substantiated to varying degrees in the studies. We are particularly interested in these competences as they can be observed, evidenced and developed. The following paragraphs illustrate some of this evidence.

Collaboration

The largest bulk in the learning outcomes pertaining to transversal competences in our review is concerned with collaboration (Bruck & Towns, 2013; Hass, 2000; Pezzementi & Johnson, 2002). In their study focusing on student interactions in the laboratory, Wei et al. (2018) found that there was an association between learning outcomes and the frequency of student interactions during laboratory work. Although most interactions observed in the laboratory were primarily concerned with procedures and results, as opposed to the chemistry behind the experiment, more interactions were observed to lead to a higher achievement level. In another study, collaborative learning was used as a pedagogical approach to examine its effect on student attitudes and performance in the laboratory (Shibley & Zimmaro, 2002). Using an experimental design methodology across three terms, they found that students in the collaborative treatment groups stayed in the laboratory longer to work on their results and seemed willing to question each other rather than relying on the professor for information. A similar effect was also reported by Pontrello (2016) and Turner, Jr. and Hoffman (2018).

Communication

Relevant to the acquisition of collaborative competence, the studies in our review also demonstrate that students learn various aspects of communication skills (Anwar, Senam, & Laksono, 2018b; Burt, 2017; Iler et al., 2012). Indeed, in studies by Díaz-Vázquez et al. (2012), Hill et al. (2019), and Li et al. (2019) collaboration and communication skills were evident in a single research setting. In these studies, students learned to articulate their ideas with clarity and communicate effectively through written and oral presentations. An interesting finding drawn from student reflections also provides an insight into student understanding of science communication and its importance in raising social awareness (Sewry & Paphitis, 2018).

A form of communication, writing is a useful transversal competence that can be developed through laboratory exercise. At face value, this competence is regarded as self-evident in laboratory education, considering most teaching laboratories use student laboratory reports as an artefact that can be directly assessed and marked. However, several studies in our review went an extra mile in substantiating learning outcomes related to writing skills that students acquired through laboratory work, as can be discerned from the works of Sampson and Walker (2012) using an argument-driven inquiry approach, van Bramer and Bastin (2013) using a progressive writing assignment, and Anwar et al. (2018a) using an orientation-decision-do-discuss-reflect method. In these studies, the researchers delved into some specifics of laboratory-related writing activities, inter alia, by attending to students' ability to justify the methods they used in the experiment and the alignment of such process with the epistemological commitments of science.

Affective domain

The affective domain in chemistry education has only relatively recently gained justified attention even though its importance has been described since the 1950s (Kahveci & Orgill, 2015). In general, this domain is concerned with such psychological constructs as values, attitudes, beliefs, perceptions, emotions, interests, motivation, and the like. One of the possible reasons why it has been studied to a lesser extent is the greater challenge in measuring the affective constructs. Conceptual and methodological knowledge of the affective domain is still developing—particularly regarding the adequacy of constructs, validation of instruments, and sensitivity of measurements. Empirical evidence for affective learning in the laboratory is, therefore, also developing. We have identified several constructs substantiated through a range of methodological approaches.

Expectations about laboratory learning

In a series of papers, a research group led by Bretz investigated students' cognitive and affective expectations and experiences of learning in the chemistry laboratory (Galloway et al., 2016; Galloway & Bretz, 2015b, 2015a, 2016). Their studies substantiate that students' expectations about laboratory learning direct their thinking and performance in the laboratory.

Their validated instrument 'Meaningful Learning in the Laboratory Inventory (MLLI)' is an attempt at an integrated perspective on student learning and assessment in the laboratory, whereby the psychomotor part of doing science should not be regarded in isolation, detached from the cognitive and affective parts. In their MLLI, the affective dimension of laboratory learning is reflected in statements such as that students expect 'to worry about finishing on time', 'to be nervous when handling chemicals', and 'to be excited to do chemistry' (Galloway & Bretz, 2015a). Mirroring their study, George-Williams et al. (2018) found that students started their university careers with very positive expectations of their teaching laboratory experiences, but these expectations became more negative each year they were enrolled in the programme.

Interest, enjoyment and engagement

In terms of frequency, affective constructs such as 'interest', 'enjoyment' and 'engagement' seem to be the most used by the authors in our review. Thirty-eight studies thematised how laboratory-related activities supported the development of student interest (Ablin, 2018; Costantino & Barlocco, 2019; Erasmus, Brewer, & Cinel, 2015), often operationalised using an attitudinal scale (Chatterjee et al., 2009; Erdem, 2015; Henderleiter & Pringle, 1999; Turkoguz, 2012). There was no singular focal point in these studies, except that they all reported on various levels of interest development—positive as well as neutral. In most cases, the term 'interest' was not used based on an explicit edifice of interest theory. Nevertheless, there were exceptions where more effort was spent on the theoretical clarification on the concept of interest. For example, Mulligan et al. (2011) situate their conceptualisation of interest in the broader scholarship of students' approach to learning (Marton & Säljö, 1976). However, they concede that their substantiation of student learning is primarily derived from students' qualitative feedback on their learning experiences, and not quantified as such. We argue that this may lend itself to a debate between methodological choice in substantiating student interest, whether there is a preference for quantitative over qualitative methods.

In most of the reviewed studies, interest was measured by asking students whether they found some intervention, activity or task interesting. And although the scope of the focus varied widely, most studies reported on (positive) interest development in the context of a course (Alneyadi et al., 2019; Kappler et al., 2017; Muryanto et al., 2017), a specific laboratory activity (Read & Kable, 2007; Zimmerman et al., 2019) or the use of a specific tool or device (Eid & Al-Zuhair, 2015; Erasmus et al., 2015; Fung, 2016). This colloquial use of the term 'interest' is a characteristic in studies that primarily focus on other factors and where interest is an *en passant* effect. However, in some of the studies found here the affective aspects like interest and enjoyment remain a focal point of the research (George-Williams, Soo, et al., 2018). In their study on inquiry laboratories, George-Williams et al. gauged students' level of interest in the experiments and found that an interesting and worthwhile experiment is key to students' enjoyment and engagement in the laboratory.

As it is the case with interest, there are several reports on positive findings regarding student enjoyment, appreciation and satisfaction (Chen, 2018; Goff et al., 2017; Tomasik et al., 2013). The same goes for findings of increased engagement in the subject or the laboratory activity (Burand & Ogba, 2013; Hartings et al., 2015; Mulligan et al., 2011; Stevens, 2017; Wilson & Wilson, 2017). In such studies, students were often surveyed in relation to an evaluation of a given course or a specific educational intervention.

In many of the studies mentioned above, student interest, enjoyment and the like were treated as one parameter that either increased or decreased due to a certain intervention. However, Ertmer, Newby and MacDougall (1996) revealed that students with contrasting goal orientations responded differently to cases they found difficult and challenging: students with a mastery orientation found such cases interesting whereas students with a performance orientation felt frustrated with these cases. This result suggests some alignment with outcomes pertaining to the mastery of a discipline presented earlier.

Self-efficacy

Self-efficacy is a specific affective construct that has been considered as particularly important in educational research. It refers to beliefs or perceptions about one's own capability to learn or perform tasks at a certain level (Zimmerman et al., 1996). In our review, seven studies explicitly mention the term self-efficacy as a learning outcome of laboratory instruction. Three of them investigate the effect of an inquiry-based or problem-based instruction on self-efficacy beliefs, and demonstrate positive results (Evans, Heyl, & Liggit, 2016; Mataka & Kowalske, 2015; Winkelmann et al., 2017). Some of these articles point to the importance of emulating some form of research experience for students to increase their self-efficacy beliefs of their ability to execute projects and solve problems. For instance, Winkelmann et al. (2017) revealed that research-inspired laboratory modules increased students' self-efficacy beliefs of their ability to complete inquiry activities. This result reflects the powerful impact of authentic research experience, which was also substantiated in the previous section on experimental competence.

Beside a full research experience, increasing self-efficacy belief was also associated with a pharmacy laboratory (Alsharif et al., 2016) and a laboratory module that included both a traditional "live" experimental component and a student-designed "virtual" computer simulation component (Goudsouzian et al., 2018). Two studies treated the relationship between self-efficacy beliefs and attitudes to chemistry (Erdem, 2015; Kurbanoglu & Akin, 2010). Both studies found a positive relationship between attitudes and self-efficacy beliefs. In their study, Kurbanoglu and Akin also looked at the relationship between self-efficacy beliefs, attitude and laboratory anxiety, which will be described in the following section.

Related to the findings on self-efficacy beliefs, many studies also report evidence of an increase in students' confidence. The increase in confidence is most often related to technical skills but occasionally also conceptual understanding. We see examples of studies demonstrating an effect from research-like educational settings on student confidence (Knutson et al., 2010) or a laboratory-intensive course that teaches students specific techniques (Witherow & Carson, 2011). We also see an example of increased confidence in a study of chemistry students in an organic practical class, where they were required to work individually, as opposed to working in groups (Lyall, 2010). The incorporation of virtual simulations and videos as a pre-laboratory activity also demonstrates that students felt substantially more confident and comfortable operating laboratory equipment (Dyrberg et al., 2017; Seery et al., 2017; Towns et al., 2015).

Laboratory anxiety

Affective constructs do not always connote a positive trait or state. Indeed, emotional states such as frustration, confusion, nervousness, boredom, anxiety and worry have been associated with laboratory work (Galloway et al., 2016). In our review, we have identified at least one of these more negatively associated affective constructs: anxiety. Focusing solely on this construct, Abendroth and Friedman (1983) implemented an actual psychological anxiety reduction programme into the chemistry laboratory sessions for first-year students and found a good effect on anxiety level. In comparison, Kurbanoglu and Akin (2010) investigated several affective constructs and examined the relationships between laboratory anxiety, chemistry attitudes and self-efficacy beliefs. Specifically, they found that laboratory anxiety correlated negatively to chemistry attitudes and self-efficacy. Mirroring this study, other studies also substantiate that different pedagogical interventions such as usage of laboratory techniques and guided inquiry reduced laboratory anxiety, while actual skills (Aydoğdu, 2017) and academic achievement (Ural, 2016) improved. The latter also observed a significant increase in students' attitudes towards the chemistry laboratory as an effect of the guided inquiry intervention.

There is an indication that the use of a virtual laboratory may reduce anxiety in comparison to a wet laboratory, although a clear effect is not established (Dalgarno et al., 2009). Similarly, the use of technology in a form of pre-laboratory video demonstration indicates that students experience less anxiety about the practical procedures in the laboratory (Teo et al., 2014). As virtual tools are getting more widely used to support learning in the laboratory, it is worthwhile to consider how they can be harnessed to not only reduce cognitive load but also laboratory anxiety.

Motivation

Motivation has often been conceptualised as belonging to the affective domain. However, its origin can be found in the research tradition of philosophy of mind, especially in its intersection with psychology. Motivation is considered to energise and direct action (Flaherty, 2020) and is seen as a precursor to the volition (Goldin, 2019). While motivation only impacts decisions to act, volition manifests as cognitive control strategies that keep a learner focused on intentions despite other opportunities and distractions.

A positive relation between increased motivation among students and an inquiry and problem-solving approach was substantiated by Knutson et al. (2010), investigating a year-long biochemistry experience. Similarly, Amante et al. (2011) found positive effects on motivation from incorporating a specific method for problem solving into laboratory activities of different engineering courses. In line with these findings, McDonnell, O'Connor and Seery (2007) find that problem-based mini-projects have increased class participation and engagement and improved class morale. Other interventions that are found to have a positive impact on student motivation are the implementation of a citizen science approach into current laboratory practices (Borrell et al., 2016), and the use of concept mapping among chemical engineering undergraduate students (Muryanto et al., 2017).

In the corpus of educational research on motivation, the learning environment is often referred to as an essential element that influences learners (van Lange et al., 2012). Deemer et al. (2017) and Park et al. (2017) treated the influence on motivation from the social environment or climate in the laboratory. Using interviews and observations of 10 students and a visiting scholar, the former revealed that the learning environment and culture in the laboratory influenced individuals' productivity and motivation to participate in research. In comparison, the latter showed that high affiliation in a laboratory session strengthened the positive association between research mastery goals and class-based mastery goals, based on surveys of 185 students using validated questionnaires.

Comparing a virtual and a traditional learning laboratory, Tarng et al. (2018) found that most students considered the virtual laboratory useful, also with regard to improving their learning interest and motivation. Likewise, de Vries and May (2019) evaluated a virtual laboratory simulation for educational use and tested if and how the virtual laboratory simulation could be applied to a practically oriented education aimed at motivating students. The overall conclusion of this study was that virtual laboratory simulation was an effective supplement to traditional teaching activities for the education of laboratory technicians. Furthermore, the study indicated that the use of virtual laboratory simulation cases increased study activity as well as motivation.

Dyrberg et al. (2017) tested a hypothesis that virtual laboratory work increased student motivation because they felt better prepared for the real laboratory exercises. They found that students did feel more confident and comfortable operating laboratory equipment, but they also found that the student did not feel more motivated to engage in virtual laboratories compared to real laboratories.

Self-regulation

Research development in self-regulation, also known as self-direction, is often aligned with reflective practice and metacognition (Sperling et al., 2004; Tillema, 2000). But more than three decades' worth of empirical and theoretical work in human motivation in a social context reveals that self-regulation is one of the most fundamental psychological needs, in which sense of autonomy and freedom to determine our own learning trajectories are crucial to our competence development (Black & Deci, 2000; Deci et al., 1996; Deci & Ryan, 2011; Ryan & Deci, 2006). In their extended work on academic achievement and self-efficacy, Zimmerman et al. define academic self-regulation as self-generated thoughts, feelings and actions intended to attain specific educational goals (Zimmerman et al., 1996). Properly designed and instructed, laboratory work provides an ample scope for developing self-regulation, provided that the experiments are not of 'cookbook' variety (Silverman, 1996). Our review substantiates this argument, as described below.

Goodey and Talgar (2016) and Seyhan (2016) found a positive effect from respectively a problem-based and inquiry intervention on students' self-regulation. Echoing this, Günter et al. (2017) found that the students took a more active role in this kind of laboratory. Positive influence on aspects of self-regulation is also found in studies conducted by Alsharif et al. (2016) in a pharmacy laboratory and Jordan et al. (2016) using student-generated video instruction.

In a thorough qualitative study using ethnographic methods Burt (2017) looked into the engineering graduate students' learning experiences to determine what students learned, and sought to identify the practices and activities related to the laboratory that facilitated their learning. It was found that research group members developed four dominant competences, one of them was receiving and responding to feedback. Another study by Hill et al. (2019) investigated the extent to which students recognised laboratory course-related skills development and understood the skills that employers are looking for. Around 10% of the students studied pointed to independent learning and study skills.

Professional identity

Three studies substantiate how laboratory work may influence students' professional identity (Nadelson, Warner, et al., 2015; Perez, Cromley, & Kaplan, 2014; Ynalvez et al., 2017). For instance, Nadelson et al. (2015) describes a study of how research experience influences the professional identity development of undergraduates. Students involved in the Research Experience for Undergraduates (REU) programme were provided with a basis for consideration of their career choices. In this programme the students were residents on campus during a 10-week summer experience where they were engaged in chemistry research. This experience allowed them to gain greater insight into the work of research scientists. Not only did REU provide students with a basis upon which they can make career plans, it also provided opportunities for students to develop their professional identity and competence. Engagement in an authentic research community influenced students' development of deeper knowledge and enhanced perceptions of themselves as science professionals.

Sjöblom et al. (2016) also found an influence on the professional identity development among students from the physical environment where they conducted their experiments, as they maintained that the usability and functionality of spaces and tools contributed to not just the fluency of the intellectual activity but also to the related emotional experience of oneself acting in a particular environment. The everyday successes or struggles in the laboratory built on the students' developing professional identity as well as their sense of belonging to the professional community.

The concept of professional identity described above is also closely related to studies seeking to understand students' choices of career paths and retention in STEM subjects. For instance, Perez et al. (2014) argue that identity development is important in college STEM student perceptions of values and cost of continuing as STEM majors. Using a short-term longitudinal survey study over one semester, they found empirical evidence showing that students' perceived cost (drawbacks associated with effort, lost opportunities, and stress and anxiety) played an important role in academic choices in STEM. Mirroring these studies, career paths and retention in STEM were also associated with work experience as laboratory assistants (Hughes et al., 2008), a laboratory course on research methods (Chen, 2018), and an undergraduate research experience (CURE) programme (Kowalski et al., 2016).

DISCUSSION

In this section, we will discuss the results of our synthesis in order to: (1) characterise learning in the laboratory; (2) provide a landscape overview of research on learning outcomes associated with laboratory instruction at university level, by identifying representations and gaps of knowledge; and (3) present implications for research, practice and theory development. The section will in general follow the structure of the results section with elaborations based on the theoretical discourse in the learning sciences and laboratory education research.

The many dimensions of learning in the laboratory

Our synthesis of 355 empirical studies on university chemistry laboratory education demonstrates that learning in the laboratory is distinctively multidimensional. The different types of learning outcomes substantiated through laboratory teaching spans several domains of learning and a range of constructs. We can discern domains of learning that involve cognition, affect, conation, psychomotor and the epistemic dimension of science. Within some of these domains, stratifications of learning are employed, such as from lower- to higher-order, basic to advanced, concrete to abstract, general to specific, naïve to sophisticated understanding, and isolated to integrated.

The notion of multidimensionality of learning is rooted in educational psychology, particularly in the critique of cognitivism, as a dominant approach to understanding human learning in the twentieth century. Dai and Sternberg (2004) assert that a cognitivist-reductionistic view on reasoning, whereby motivation and emotion are seen as peripheral to cognition, disregards essential components of intellectual functioning and development. In a real-life context, learning is a dynamic, multifaceted phenomenon that may only be understood properly when all related elements are considered. Accordingly, as a complex phenomenon, it is affected by a host of motivational, emotional, self-regulatory and phenomenological aspects (Illeris, 2018). In chemistry education, this notion has also been explored in large-scale studies and curriculum reforms, highlighting the importance of redirecting science instruction towards integration of content knowledge and scientific practices (Cooper & Stowe, 2018; Pazicni et al., 2021; Stephenson et al., 2020) and theorised further to frame a comprehensive assessment of learning in the laboratory (Agustian, 2022). Our synthesis provides insight into the dimensions and underlying constructs employed in current research.

The manner in which those learning domains have been substantiated still necessitates integration. One of the most perpetuated learning goals in the laboratory is the theory-practice connection, whereby students are expected to obtain an understanding of the underlying theoretical, conceptual and epistemic assumptions during laboratory work. Getting students to have 'minds-on while hands-on' is still a challenge to laboratory education practitioners, and it is reflected in our review. When this lack of integration is extrapolated to a broader landscape of learning domains, considering students' conation, affect and social construction of meaning, it seems clear that the potentials of meaningful laboratory learning have not been reached. This problem may be caused by a fragmented approach to curriculum design, instruction and assessment. In seeking to improve the quality of laboratory education, both researchers and practitioners involved in teaching laboratories should aim at a high level of integration of these learning domains. From the perspective of curriculum development, this will ensure coherence between the three levels of curriculum, namely intended, implemented and attained levels (Thijs & van den Akker, 2009), as argued at the beginning of this review. From the pedagogical perspective, stronger integration could lead to more meaningful learning and holistic experience of doing science (or learning to do science) in the laboratory (Dai & Sternberg, 2004).

Experimental competences and laboratory skill performance assessment

Over the course of more than a century, teaching laboratories have been established as a place to learn to do science (Bretz, 2019; Hofstein & Lunetta, 2003; Kirschner & Meester, 1988; Seery, 2020). The activities of preparing for an experiment, planning an inquiry, executing it, analysing the collected data and reporting the results, require a lot of knowledge and skills, which renders laboratory learning distinctive. Nevertheless, critics often lament the lack of assessment of, for example, laboratory techniques and practical skills (Agustian, 2020a, 2022). The psychomotor domain is often hailed as the *raison d'être* of laboratory education, but although laboratory work in university chemistry courses often involves skills such as manipulating glassware and performing instrumental techniques, assessments are not always designed to measure students' performance of these skills and techniques. This is mirrored in our review. To illustrate, about a third of the studies mention learning outcomes related to experimental competences. Of this, the actual practical skills performance has been assessed to an even lesser extent (51 out of 355 studies, or around 14%). If the psychomotor domain lies at the heart of laboratory pedagogy, why is it not assessed adequately?

A part of the answer may be that many basic practical skills such as titration and distillation are becoming obsolete and are being replaced with automated systems. Therefore, the importance of these basic skills in scientific practice is diminishing. However, if they are part of the laboratory curriculum and the longer progression of student learning trajectories, we argue that they should be assessed. If students are taught and make efforts to develop those skills, they should receive feedback on how their learning is progressing. Of course, this is primarily relevant for laboratory courses offered to science majors and presumably less so for those aiming at non-science students.

The assessment of practical skills and laboratory techniques is evident in our review, but it is mostly an indirect assessment, in which students' self-reports are used to gauge their perception of skill level, as described in the results (Carson & Miller, 2012; Warner et al., 2016). In cases where direct assessment is administered, it is mainly an assessment of content knowledge, with a few exceptions of observations of behaviour in the laboratory, including using video registration (Galloway & Bretz, 2016; Harsh, 2016). The self-reports are usually generated from interviews or surveys, where students are asked to what degree or if they think they became better at performing at certain laboratory-related task. Such reports are important mainly for establishing and attending to students' self-beliefs and self-efficacy in the laboratory, two constructs primarily associated with the conative domain of learning. However, a proper practical assessment that works well on many levels is not easy to design and implement. Several authors have tried and succeeded (Kirton, Al-Ahmad, & Fergus, 2014; Towns et al., 2015), but today's reality of science courses admitting large numbers of students each year often forces laboratory course designers to employ conventional written tests rather than actual performance assessment of practical competences. Thus, there is a need to reconsider the types of summative assessment employed by institutions and for students and institutions to shift the focus towards the continuous formative assessment, rather than summative assessment.

Laboratory instruction and corresponding assessment should be directed towards higher-order experimental competence, defined here as competence related to designing an experiment. This will address the problem of students just following predesigned protocols that is often associated with a 'cookbook' approach to laboratory curricula.

In our conceptualisation of experimental competences, we refer to inquiry as a pedagogical and methodological approach to *learning to conduct* scientific investigations. Due to the nature of progression of most undergraduate degrees in science, inquiry-related competences such as experiment design, critical evaluation of data and argumentation will be indispensable, because towards the end of their degree, students are typically expected to conduct a full inquiry on a scientific theme of interest (Seery et al., 2019). Surely students cannot be expected to acquire this competence without experience of planning, executing, evaluating and reporting a scientific investigation. In the case of laboratory education, the execution part entails practical skills and laboratory techniques, and we assert that these need to be assessed adequately as well.

Pre-laboratory work plays an important role in facilitating the experimental competence acquisition and cognitive learning. We have identified recurring foci on pre-laboratory activities and their role in providing scaffolding on both theoretical and practical accounts (Chaytor et al., 2017; Darby-White et al., 2019). Students are usually urged to prepare their laboratory session by reading the laboratory manual, reviewing related concepts from lectures, and becoming familiar with the techniques and manipulations of the experiment, but typically far from all students actually do so (Agustian, 2020a). Lack of preparation is one of the factors that causes anxiety during the laboratory work (Kolodny & Bayly, 1983). Johnstone et al. (1998) posit that the aim of the pre-laboratory activities is to prepare students to take an intelligent interest in the experiment by knowing where they were going, why they were going there and how they were going to get there. In a previously published review, Agustian and Seery (2017) argue that pre-laboratory activities have been used on the grounds of at least three rationales, namely to introduce chemical concepts, to introduce laboratory techniques and to address affective dimensions. This systematic review confirms the findings. Pre-laboratory work should be designed within an appropriate pedagogical framework to ensure progression from pre- to in- to post-laboratory by means of scaffolding.

Disciplinary learning outcomes: need for more focus on higher-order cognition

Unsurprisingly, our synthesis shows that chemistry-specific outcomes are strongly represented, with more than half of these studies associated with some form of disciplinary learning. A tendency is that much of what is measured pertains mainly to lower-order cognition and many studies are focused mainly on content knowledge. In the critical analysis of the quality of the studies, we identified several published articles that had quality issues. Some were based only on course evaluations, some lacked clear formulation of research questions or hypothesis, some failed to employ appropriate use of relevant educational theories, some lacked methodological rigour. There is scope for more investigation into higher-order cognition in laboratory settings. In our review, this is exemplified in several well-designed studies that focus on problem solving and argumentation in the laboratory, in which students use core concepts to construct arguments, explain a phenomenon and solve a problem.

We have found a large number of studies where students' conceptual understanding was measured, as specified in the results section. Likewise, some of the studies focused on higher-order thinking skills and related constructs, namely problem solving, critical thinking and metacognition. The importance of attending to complex cognitive tasks and higher-order skills is that these skills are required in the acquisition and development of competence, whereby highly integrated knowledge structures, interpersonal skills, attitudes and values work in synergy (van Merriënboer & Kirschner, 2017). The integration of these skills into laboratory exercises is possible precisely because of the complex nature of the learning environment (Seery et al., 2019). Thus, while the complexity of the environment is often considered detrimental to learning, it also holds potential for the development of higher order thinking.

In developing effective instruction to address higher-order cognition, it is important to consider relevant theories as a framework of reference. For example, regarding argumentation, science educators may focus on argumentation as a critical element in the design of learning environments in order to make scientific thinking and reasoning visible (Duschl & Osborne, 2002). As such, students should be encouraged to explore critically the coordination of evidence and theory that support or refute an explanatory conclusion, model or prediction, much of which is pertinent to laboratory work.

Transversal competences: need for more focus on social and epistemic domains

In the literature of laboratory education, generic skills, transferable skills or transversal competences are often lauded as one of the valued potentials of laboratory work (Hodson, 1993; Johnstone & Al-Shuaili, 2001; Reid & Shah, 2007; Seery, 2020), albeit with some reservation (Wellington, 2005). In our review, these competences are represented by collaboration and communication, but the constructs related to higher-order thinking skills could be also interpreted as transversal.

The reference to constructs such as argumentation, collaboration and communication shows that the social domain of learning is clearly a characteristic of laboratory education. However, this is more often assumed than actually studied (Nakhleh et al., 2002). We identified a gap in our understanding of how social interactions facilitate students' chemical learning, that is, relating the three levels of chemical representations (macroscopic, submicroscopic and symbolic), which is a typical problem in chemistry education (Johnstone & Al-Shuaili, 2001).

There is still much scope for investigation into various aspects of social interactions in the laboratory. Of great interest is the kind of interactions that involve artefacts such as laboratory instruments. We still have limited understanding of how learning unfolds and extends from the personal to the social in a learning environment where instruments and equipment are used to perform learning tasks (Agustian, 2022). With more research-based knowledge in this area, for example in distributed cognition (Hutchins, 2001), curricular and pedagogical interventions could be directed towards increasing the use and usefulness of the social and material interactions to enhance learning experiences in the laboratory. Also in relation to the social domain, our current understandings in the learning sciences and science studies highlight the importance of finding a balance between teaching for conceptual, epistemological and social learning goals (Duschl, 2008; Duschl & Grandy, 2013).

We described how the epistemic domain has been addressed primarily in terms of students' understanding of the nature of science. In the university setting, there is certainly a need to understand the role of the laboratory for student learning about how knowledge is established in the sciences (Agustian, 2020b). The 'material turn' in the philosophy of science—stressing the complex interplay between material, technologies and theory development—has shed new light on the crucial role of the experiment and the experimental process in the overall scientific development (Hacking, 1983; Latour, 1986; Pickering, 1995). However, the implications of this renewed focus on the role of the material aspects of scientific knowledge production has not yet impacted laboratory education research.

Engaging students in epistemic practices of science is pivotal to the deep understanding about the nature of their disciplines through participation (Matthews, 2018). However, 'cookbook' laboratory procedures do not necessarily help students develop knowledge and understanding of the scientific knowledge creation process. We argue that research can play a role of organising the efforts so that students have an opportunity to reflect on some of the epistemic dimension and problems related to their laboratory work (for instance, concerning research conduct, inter-subjectivity and so forth).

The affective domain: need for more theoretical grounding

Our analysis shows that a relatively large number of studies report on aspects of affective learning. Thus, there is a substantial emphasis on the affective domain in the description of laboratory-related competences. However, although we have coded seven distinctive constructs, some of them were presented as a lay-term or in a not very theoretically informed manner. For instance, statements in the results section along the line of 'Students *enjoyed* the laboratory work' or 'They were *interested* in the new laboratory structure'. This is particularly true for studies involving self-reports in data collection. Sometimes the indication of affective response is perhaps simply expressing the subjectivity that student self-reporting entails, rather than an actual investigation of the role of a specific affective construct for learning.

STEM education scholars have highlighted the importance of attending to the affective domain of learning and instruction, including in a laboratory context (Alsop, 2005; Chamberlin & Sriraman, 2019; Kahveci & Orgill, 2015; Wellington, 2005). In the context of constructivist pedagogy, this domain is often associated with the question of *how* students experience learning, as opposed to *what* they learn. It is difficult to think of the affective domain in isolation from the cognitive. In the context of our argument for more integration of learning domains, researchers and practitioners should consider affective factors in laboratory instruction. An attempt at integrating the cognitive and affective domains of learning can be discerned from the work of Oatley (2000) which is highly relevant for laboratory education due to its close association with distributed cognition. This is illustrated in the way long-term emotional states such as enjoyment, enthusiasm and affectionate warmth can influence learning through mobilisation of resources and maintenance of commitment to the learning goals, particularly in the context of social interactions involving artefacts in laboratory learning environments.

IMPLICATIONS

Implications for research

Findings from this systematic review provide a roadmap for future studies in laboratory education. Learning in the laboratory is multidimensional, and future research should be directed towards a more comprehensive substantiation of student learning that considers different learning domains, the interplay between them, and ways in which they could be enhanced. This includes (1) considerations of all learning domains associated with laboratory work, namely cognitive, affective, psychomotor, social and epistemic; (2) use of both direct measures, such as rubrics and observation protocols, and indirect measures, such as validated questionnaires (Demeter et al., 2019); and (3) focus on not only learning outcomes but also learning processes, including constructs regarded as prerequisites for learning. As discussed, a higher level of integration between the different learning domains in substantiating student learning could also improve our understanding of the interplay between aspects of learning and how they could support each other. For example, when designing a research instrument to measure a specific cognitive construct, it is important to bear in mind that cognitive processes in the laboratory are not isolated and devoid of a broader context of learning. Thus, larger-in-scope constructs such as epistemic practice (Kelly & Licona, 2018) and scientific inquiry (Hodson, 1996) are relevant.

Research endeavour to improve rigour and relevance is argued to strengthen the evidence for student learning in the laboratory and the quality of laboratory education research in general (Lodge & Bonsanquet, 2014; Van Merriënboer & Sweller, 2005). There is strong evidence for the added value of laboratory work in higher science education compared to a less expensive format such as lectures, as described in the results. However, some of the evidence discerned from the included studies could benefit from greater methodological rigour. Triangulation is particularly relevant and important for a more comprehensive understanding of student learning in the laboratory. Data obtained by different means would have strengthened the findings.

There is a need for further studies in higher-order cognition and epistemic learning in the laboratory, particularly metacognition and social epistemology. The laboratory is a fertile field of research, primarily due to its complex nature, and we still have a limited understanding of social-epistemological aspects of teaching and learning in this setting. We need to better understand how the social interactions in the laboratory, either among students, between them and the instructors, and between both and the instruments, influence personal beliefs, knowledge and competences. There is little knowledge as to whether and how the widely practised grouping in laboratory work elevates the personal to the social and how it contributes to learning. In terms of conceptual clarity, the construct 'critical thinking' may need to be defined more clearly, especially when it is part of the investigation or reported as a learning outcome.

Correspondingly, a better understanding of how students develop their higher-order experimental competences is needed. Scholarships in science studies and the learning sciences may prove to be a useful body of knowledge to consult. A few studies have been published (Anagnos et al., 2007; Goodey & Talgar, 2016; Lefkos et al., 2011), but there is a large scope for more rigorous intervention studies in which students are adequately supported in their development of experiment design competences. This is crucial also from a practice perspective, as we elaborate next.

Implications for practice

For laboratory curriculum designers, it is important to develop a curriculum that accommodates and fosters students' progression of learning, as mapped in our review. Consider, for example, students' development of experimental competences, from acquisition of basic practical and data-related skills to a more advanced ability to design an investigation. To be able to design an experiment, students must be proficient and confident with basic skills and procedures needed for the design. Therefore, both have a place in the curriculum. A pitfall in much laboratory instruction is that this progression is not scaffolded, or worse, entirely disconnected in the curriculum. If the preceding laboratory courses are entirely prescribed for students, students dislike being required to design their own scientific inquiry towards the end of their science degree (Agustian, 2020a). They need to be exposed to an increasingly higher level of inquiry as they progress in their higher education (Etkina et al., 2010).

For laboratory instructors, it is important to revisit assessment and feedback practices in the laboratory. As argued in this review, the learning continuum related to laboratory instruction starts before students enter the laboratory and continues after the exercise has been completed. While the practice of pre-laboratory activities has been prevalent at least since the 1970s (Agustian & Seery, 2017), they are not always assessed, and students do not always get feedback on their pre-laboratory work (Chittleborough et al., 2007). *Formative* feedback and assessment practice to support students' competence development should be a central focus and permeate the learning continuum mentioned above. For instance, although laboratory reports are widely adopted to document students' laboratory work, there is still a need for empirical investigations of how feedback on these reports impacts on students' understanding of the experimental work they have carried out.

Implications for theory

As a part of science education research, laboratory education research has a large potential for theory development. We have identified at least three areas in which relevant theories could be developed, departing from this review. Firstly, epistemology in higher education. Experimental work has been a central and largely influential element of scientific knowledge development. To date, parallels between the inner workings of science and educational practices that reflect these workings have been studied (Berland et al., 2016; Jiménez-Aleixandre & Crujeiras, 2017; Knorr-Cetina, 1999), but there is arguably a large scope for research and development in the context of laboratory education. A useful work is, for example, Jiménez-Aleixandre and Reigosa (2006). Future work on epistemic orientation in this context can advance theoretical development in philosophy of science, particularly the intersection between philosophy and education.

Secondly, the learning sciences. The complex nature of learning environments in the laboratory lends itself to various foci, depths and levels of interdisciplinarity. The cognitive-psychological focus that permeates the scholarships in science teaching and learning could be enriched with the social- and cultural-psychological foci. The manifestation of embodied learning in the laboratory may also further our understanding of bodily and perceptual experiences involved in science learning. Accordingly, the affective and conative domains of learning in the laboratory represented in our review with constructs such as self-efficacy beliefs and motivation may contribute to a more nuanced understanding of how related theory such as self-determination theory (Deci & Ryan, 2011) can be contextualised in scientific practices.

Thirdly, curriculum theory in higher science education. We purposefully make references to curriculum design and development as an important framework in which researchers and practitioners could work (collaboratively) on student learning outcomes and processes. The notions of inquiry, scaffolding and competence development are chief to the theoretical and methodological choices made in the primary studies. Synthetic work such as this systematic review has an implication for a more thorough overview of the central role of curriculum development in university science education.

CONCLUSIONS

We have systematically reviewed empirical studies focusing on student learning outcomes in the chemistry laboratory at university level. Based on established criteria, we have identified five large clusters of learning outcomes: experimental competences, disciplinary learning, higher-order thinking skills and epistemic learning, transversal competences and the affective domain. Each of these clusters have been specified and described. Firstly, disciplinary learning in the laboratory is related to conceptual understanding, theory-practice connection, academic achievement and mastery of chemistry. Secondly, experimental competence pertains to experiment design, conducting an experiment, laboratory skills and techniques, as well as data analysis and interpretation. Thirdly, higher-order thinking skills are concerned with problem solving, critical thinking, argumentation, metacognition, reasoning and reflection, as well as epistemic learning. Fourthly, transversal competences identified in our review are collaboration and communication skills. Finally, the affective domain associated with laboratory instruction manifests as learning expectation, interest, enjoyment and engagement, self-efficacy beliefs, laboratory anxiety, motivation, self-regulation and professional identity.

Our analysis of published studies led to a substantiated view of multidimensional learning in the laboratory, in which the conceptualisation of student learning goes beyond the cognitive view. With considerations of the affective, conative, psychomotor, social and epistemic dimensions of learning, our synthesis reveals a broad landscape of research on student learning, with areas deserving appraisals and gaps of knowledge yet to be resolved. Several issues related to each of the identified constructs have been discussed in light of contemporary scholarship in learning sciences and STEM education research. We have presented recommendations for future research to focus more on higher-order cognition. Likewise, we have identified a sizeable scope for developing and assessing higher-order experimental competence that goes beyond indirect assessment of skill level perceptions. We have also identified various constructs belonging to the affective domain but there is a need for more theoretical grounding in current scholarship in the affective dimension of chemistry education, a field of research that has only recently gained the relevant attention. Transversal competences are well substantiated in our review but there is room for more focus on the role of the social and epistemic domains of learning in the laboratory.

Our review sheds some light on how virtual laboratory has been used, and it is pertinent across the clusters of learning outcomes we have identified. There is a modicum of evidence for its benefit in terms of conceptual learning, self-efficacy beliefs and motivation. However, most of the studies used it in combination with the physical laboratory, either in the form of pre-laboratory activity or a supplementary simulation resource, as opposed to a substitute for the real experience. As the world witnessed the Covid-19 pandemic, faculty worldwide were forced to immediately shift laboratory teaching online. We completed our search process prior to this unprecedented situation, and as we worked on the analysis and synthesis during the lockdowns, a multitude of studies on laboratory education which were presumably entirely virtual are not included in this review. Therefore, there is a scope for an extension of this systematic review to also explore laboratory education where laboratory work is not present. See, for example, Kelley (2021), Finne et al. (2021), and other special publications in *Journal of Chemical Education*.

In general, research development in laboratory education necessitates more rigour in terms of theoretical and methodological frameworks. We have identified specific areas where this could be enhanced, such as formulation of research questions, clear theoretical framing, relevant triangulation, and clarification of the construct definitions. Implications for practice have been suggested, particularly concerning curriculum design and assessment. Likewise, we have proposed implications for theory development in philosophy of science, the learning sciences and curriculum theory in higher education.

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CONFLICT OF INTEREST

There are no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

ETHICAL APPROVAL

As this research is based on a systematic review of published studies, ethical approval is not applicable to our research.

ORCID

Hendra Y. Agustian https://orcid.org/0000-0003-2792-3035
Laura Teinholt Finne https://orcid.org/0000-0002-5015-7079
Jonas Tarp Jørgensen https://orcid.org/0000-0003-1004-5942
Frederik Voetmann Christiansen https://orcid.org/0000-0002-6743-9881
Bente Gammelgaard https://orcid.org/0000-0002-9149-1014
Jan Alexis Nielsen https://orcid.org/0000-0002-2596-4880

ENDNOTE

[1] The American Educational Research Association, https://www.aera.net/Education-Research/Beyond-AERA/Education-Resources-Information-Center

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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Appendix 2 : Paper 2 – Tid til læring i laboratoriet: farmaceutstuderendes opfattelse af tiden i laboratorieundervisningen

Learning in the laboratory: how pharmaceutical science students perceive time in laboratory instruction

Laura Teinholt Finne, Department of Pharmaceutics and Analytical Chemistry, University of Copenhagen, laura.finne@sund.ku.dk

Bente Gammelgaard Department of Pharmaceutics and Analytical Chemistry, University of Copenhagen, bente.gammelgaard@sund.ku.dk

Frederik Voetmann Christiansen, Department of Science Education, University of Copenhagen, fchristiansen@ind.ku.dk

Abstract

Laboratory instruction is an integrated part of many natural science education programmes, especially within chemistry and pharmaceutical programmes. In the present study, we have attempted to identify how pharmaceutical science students perceive learning in the laboratory through individual, semi-structured interviews with six students. The interviews provide insight into how the students experience the laboratory instruction and provide perspectives on their perception of, and approach to, the laboratory teaching, as well as into how exams affect their behaviour. A recurring theme in the students' statements about the laboratory instruction is how they experience and perceive the quality of the time spent in the laboratory. There are substantial qualitative differences between how the individual students describe this time. Some students perceive time spent in the laboratory as time for reflection and learning, whereas others perceive it is a waste of time. How the students perceive time in the laboratory greatly affects their learning and how they prepare for their exams.

Introduction

The teaching laboratory plays an important role in chemistry, biochemistry and pharmaceutical science education at university level. Historically, the manual and technological aspects of these subjects have been given high priority in the education of skilled practitioners who are to work in industry, pharmacies and the public sector. However, because many processes have been automated, today's labour market has less use for the specific practical skills of a chemist. Because of this, laboratory instruction is now more geared toward teaching students adequate practical skills, and toward ensuring that they acquire conceptually oriented competencies within specialist quality-assurance tasks and development tasks. For this reason, laboratory instruction has remained a central part of chemistry-oriented university programmes.

Laboratory courses play a central role with regard to students learning the ways of thinking and practising in their subject (Mccune &Hounsell, 2005). During their studies, students are socialised into understanding and conceptualising academic problems based on academic practices. Such practices include knowledge, subject-specific competencies and skills, acknowledgement and understanding of the values of the discipline, understanding and recognising the scholarly communication within the discipline, as well as understanding how new knowledge is generated within the field (Hounsell & Hounsell, 2007; Mccune & Hounsell, 2005). The notion that specific ways of thinking and practising exist stems from the British ETL study (Enhancing Teaching-Learning Environments in Undergraduate Courses, Entwistle, 2014; Hounsell et al, 2005). This relatively large-scale study was launched in the early 2000s, and it examined teaching-learning environments across subject areas and institutions.

Part of the ETL project concerned undergraduate students' experiences of bioscience courses. Interviews with the students showed that it was especially toward the end of their study programme that the students became aware of the ways of thinking and practising in their subject, and that working with primary literature and experimental data seemed to play a particularly important role in this awareness (Hounsell & Hounsell, 2007). The practical work in teaching laboratories was highlighted as being particularly important for obtaining this insight, even though the ETL project did not include laboratory courses (Mccune & Hounsell, 2005, p. 264).

In this study, we focus particularly on the learning that takes place in laboratory courses. Our study is part of a larger project about students' perspectives on which factors influence how pharmaceutical science students acquire laboratory-related competencies.

In the present article, based on a phenomenographic research approach, we examine the students' experiences of laboratory instruction. The phenomenographic research tradition seeks to understand how a phenomenon is experienced, and focuses on the differences and *variations* in the experience (Marton, 2014; Marton & Booth, 1997). The assumption is that a limited number of qualitatively different ways of experiencing phenomena exist; these different ways are called categories. A phenomenographic analysis results in a description of these categories and the differences between them. The purpose of this analysis is to examine how individuals from a specific group experience a phenomenon differently. Thus, a so-called second-order perspective is taken in that focus is on the variations in how the phenomenon is experienced and conceptualised by a group of individuals. This stands in contrast to a first-order perspective in which focus is on the phenomenon examined (Marton, 1981).

It is important to note that each individual in the study is not necessarily represented in only one category. The categories describe the collective perception of the phenomenon, and individuals will seldom have perceptions and approaches that only match a single category; rather, their approaches may change depending on the given context. As Marton (1981) puts it: "*the same categories of description appear in different situations. The set of categories is thus stable and generalizable between situations, even if the individuals 'move' from one category to another on different occasions.*" Thus, the students may describe experiences that fit into several categories, depending on the context. That is, the categories cannot be seen to express a personality trait, but rather present an image of the different ways in which the phenomenon is experienced.

In a phenomenographic study of how students perceived a project-oriented course in organic chemistry, Burrows et al. (2017) identified eight different approaches to the teaching at four different levels. Other qualitative studies that examined how students experience the learning environment in the teaching laboratory have focused on the students' goals for laboratory instruction and the affective aspects (DeKorver & Towns, 2015; Galloway, Malakpa, & Bretz, 2016; Russell & Weaver, 2011).

The present study used the phenomenographic approach to gain insight into the *students'* perspectives on how laboratory instruction affects their learning experience. The students' perspectives are important, because their experience of the course may be very different from the instructors' intentions and experiences. We therefore seek to answer the following research question: *What factors influence how students experience learning in laboratory instruction?*

Our study differs from previous studies because we examine another type of course than the previous studies and we focus on how students experience the cohesion in the learning environment (congruence, see below).

Method

The data for this article is taken from a pilot study, the objective of which was to qualify the interview guide for a subsequent larger study. Semi-structured interviews were conducted with six pharmaceutical students in autumn 2019. The focus of the interviews was how the students experienced learning in the laboratory course *Pharmaceutical Analytical Chemistry*.

The interview guide was inspired by Hounsell & Hounsell's (2007) congruence model, which describes the important interplay between aspects of the teaching-learning environment and students' backgrounds and aspirations, and how this interplay determines the way in which students think and practise, and thus the quality of their learning outcomes (see Figure 1). The concept of *congruence* describes a link or consistency (Ulriksen, 2014). The congruence model can be seen as a further development and generalisation of the concept of *constructive alignment* (Biggs & Tang, 2011), which only covers congruence between aims, teaching-learning activities and assessment.

Figure 1 Hounsell & Hounsell's (2007) congruence model. The link between the aims, teaching-learning activities and the exam is generally referred to as constructive alignment, but also a number of other factors affect students' opportunities for developing high-quality learning. Moreover, how a course is organised, the support available during the course, and the students' prior experiences are also important elements for developing academic ways of thinking and practising, and thus achieving high-quality learning.

Students' backgrounds & aspirations
Assessment & feedback
Course organisation & management
Aims, scope & structure
Teaching-learning activities
Learning support

The interviewer began the interview by asking open-ended questions in an attempt to discuss with the student all the dimensions of congruence. At the end of the interview, the student was shown a simplified version of the congruence model and was given the opportunity to comment on each of the congruence dimensions. The overall theme was learning in the laboratory course, and the students were asked, to describe the structure of the course and the link between the individual course elements. In addition to the overall questions, the interviewer focused on the link between the course and the exam. For example, the students were asked whether they could recognise any elements from the course in the exam questions.

The interviews lasted between 38 and 53 minutes and were recorded and subsequently transcribed. The interview transcriptions were read and re-read with an open approach to identify any cross-cutting topics that the students mentioned themselves. The material was then coded in relation to these topics as well as to the congruence dimensions from Figure 1. The interview transcriptions or audio recordings were consulted several times during the analysis process to ensure that the interpretation was in line with what the students had said. The interviews and the analysis were conducted by the first author and subsequently discussed and interpreted by all the authors. One of the authors is both the course coordinator and one of the instructors on the course; according to her, the students interviewed are a fair representation of the students on the course.

At the time of their interview (5th semester), the students had completed the course and exam in *Pharmaceutical Analytical Chemistry*. The students were from different classes and groups, and comprised three women and three men. Approximately 75% of the students enrolled in pharmaceutical sciences in Denmark are female. The students voluntarily enrolled in the study after having been encouraged to do so during a lecture and a laboratory class. All participants were informed in writing that they could withdraw from the project at any time. See Figure 2 for a brief description of the course module.

Content and materials of the course module: The course *Pharmaceutical Analytical Chemistry* is a mandatory course in the fourth semester of the bachelor's programme in pharmaceutical sciences, University of Copenhagen, and is a 7.5 ECTS credit course. The course is scheduled as 19 45-minute lectures plus 72 hours in the laboratory (18 x 4 hours). The laboratory course module (2.5 ECTS) is passed based on assessment of eight lab reports and a course certificate is issued, whereas the theoretical course module (5 ECTS) is passed with a grade based on a 3-hour written exam with all aids allowed. The written exam is assessed by the instructor and an external examiner. Written material for the course consists of a textbook in English and a compendium in Danish, which describe the knowledge required to conduct the exercises and the exercise descriptions. Furthermore, the course homepage contains a number of videos that describe the theory, as the lectures are increasingly used for interaction with the students. The course homepage also includes previous exam questions with answers provided, as well as practical information.

Laboratory instruction: There are 8 teams of approximately 25 students, and each team has their own instructor. Two teams work in the laboratory at the same time. The students work in groups of 2-3 that they form themselves at the beginning of the course. The laboratory instruction consists of 8 modules that each comprises one or more exercise sessions, and the teams take turns at using the equipment because the lab does not have enough equipment for each team to have its own set up. In several of the modules, time is allocated to preparing an experiment plan, to conducting the analyses, and to processing the data and writing the report. Data processing often requires specific software that the students only have access to in the laboratory. The course is planned so that the students have a lot of time in the laboratory. This means that a substantial part of the students' face time with instructors and laboratory technicians takes place in the laboratory. Students receive feedback on their reports from the instructor during laboratory class. The course does not include separate class sessions. The laboratory is spacious with room for large desks and workstations that are connected to a network. See Figure 3.

How the course fits in with the other classes: On average, the bachelor's programme includes two laboratory courses of varying length in each semester. This means that students have extensive experience with laboratory courses, and during the interviews, they sometimes refer to previous experience with laboratory coursework. If a quote refers to any other course than the course *Pharmaceutical Analytical Chemistry*, this will be indicated in the analysis. Students use the competencies obtained from the course in subsequent courses offered in the fifth and sixth semesters, including in their bachelor-programme projects.

Figure 2 Brief description of the course Pharmaceutical Analytical Chemistry.

Figure 3 Room adjacent to the chemistry laboratory in which the students prepare their experiment plans and write their reports with help from the instructors. Several students can be seen in the background using some of the equipment and software available in the main laboratory. All the students in this photo have given written consent allowing the University of Copenhagen to use images of them in information and recruitment materials.

Analysis and results

The analysis and the results are based on the codes derived from the congruence areas and comprise the dimensions *Time; Learning support; Teaching-Learning Activities; Assessment and Feedback;* and *Approaches to Learning* and *Perceptions of Learning*.

The code *Time* is the only crosscutting theme that has been included in the analysis. *Time* is a recurring theme in the interviews with the students, and the interviews show that the experience of the quality of the time spent in the laboratory – and management of the time in the laboratory – play an important role for how the students perceive learning in the laboratory. In the analysis, we will begin by showing how the experience of time in the laboratory affects the experience of cohesion in the learning environment, see Figure 1.

Scheduled time and personal time

Ylijoki and Mäntylä (2003) examined how researchers experienced time, and they distinguished between these four core experiences of time: scheduled time, timeless time, contracted time and personal time. Liao et al. (2013) examined how students experience time and defined six different categories: scheduled time, compressed time, timeless time, endless time, wasted time, and time as goal. In the present study, we see that overall the students distinguish between *scheduled time* and *personal time*, similar to Ylijoki and Mäntylä's finding in their study of researchers.

For example, one student made this very explicit distinction between the two categories of time:

"I'm really an 8 to 4 kind of person, so I get up early and get something done if I don't start class until 10. But that means I stop at 4-5 o'clock. [...] it's important to me to have some free time. To have time to work out and hang out with my friends and do other stuff than just study." (D05)

The same student also describes how they strive to allocate a reasonable amount of time for studying – and even more time than scheduled by the university – however, it is important that this time does not encroach on their personal time.

Another student does not make the same explicit distinction between scheduled and personal time; rather they talk about spending a considerable amount of time preparing. However, this time is not spent on preparing for laboratory instruction, but rather on preparing for other subjects that require a lot of preparation in the form of reading and doing assignments:

"I spend my time in the lab and in lectures. But I didn't spend a lot of time on it at home compared to some of the other subjects. [...] and it was more [reading] that I spent time on at home [...]. We also had class sessions in those subjects, and we had to do assignments. And I often worked on these at home. [...] I could easily spend an entire Sunday working on those assignments. [...] and then it was ***actually quite nice, that in this subject, that I spent a lot of time on it at the university*** *[...] that is, it doesn't take long to read the instructions in the compendium." (D02)*

For this student, it is positive that the time spent on preparing for laboratory instruction is physically delimited and scheduled.

How scheduled time is experienced: reflection time or wasted time?

When the interviews focused on the students' experiences in the laboratory, the students comments centred on scheduled time. Formal scheduled time is characterised by being planned by an institution (Liao et al., 2013), but how the students act within the set framework varies from student to student. Some of the students just want to get it over and done with:

"You've got LAB from 8 to 12 and then again from 12:30 to 16:40, right. You just need to get it over with." (D01)

Another student mentions that in laboratory courses scheduled time is actually often characterised by having a lot of wasted time, but that this was not the case for this course:

"But there wasn't... It wasn't noisy and there weren't a lot of people. You didn't have to stand in line for things and stuff like that. [...] everything was calm. [...] you felt like you weren't wasting your time, [...]." (D03)

Overall, the students experience more time pressure in other laboratory courses. This has led them to being very focused on completing the practical aspects of the course; however sometimes this negatively affects their understanding:

"*... but in general, there's almost never enough time to actually understand what you're doing." (D06)*

Nevertheless, this student perceives the time spent in the course Pharmaceutical Analytical Chemistry as *reflection time*, whereas this is not always the case for other courses.

Some students see this laboratory course as an opportunity to gain a deeper understanding within the scheduled time, and as such, they experience the time in the laboratory as *reflection time.* Others see the work in the lab as something that they just need to get done; overall, these students experience the time in the laboratory as *wasted time*. These two perceptions show two qualitatively different ways of experiencing time in the laboratory, and the students manage the scheduled time differently depending on which perception they have.

There is more or less an equal number of students in each of the two categories. Two students (D01 and D05) primarily experience the time in the laboratory as *wasted time*. Two other students (D03 and D06) primarily experience the time in the laboratory as *reflection time*. Finally, the remaining two students (D02 and D04) do not fall into either as their perceptions fit both categories depending on the situation. This supports the claim that the students' inherent nature – or personality traits – do not determine which category they experience belonging to. Rather, this is determined by an interaction between the experience of congruence in the six different dimensions (see Figure 1), including the approaches the students have to the subject. For example, in this course, student D03, who is quoted above, thus experienced time in the laboratory as *reflection time* compared with other laboratory courses in which time was experienced as *wasted time.* This indicates that the other congruence dimensions, including course management, may significantly impact the students' experiences.

How teaching activities are experienced

Some students experience that the practical exercises take up too much time, and they fail to see the correlation between the work they do in the laboratory and their learning. They feel that they have to hurry up, and that the practical work takes time away from more important activities. This experience is linked to the experience of time in the laboratory as *wasted time*.

"*There's all the practical stuff that needs to be done. And this... this sort of gets in the way of thinking about the theory, because there's so much practical stuff […]. I'd more or less spent all my time on getting the LAB exercises done and handing in the reports without really understanding 100% what I'd been doing." (D05)*

"[...] you've rushed everything in the lab, and rushed to get the report done, and it really only needs to be passed, because you just want to get it over and done with." (D02)

The first quote shows that this student is aware of the potential for learning through the exercise, but that this potential is not realised because of the practical things that must be *done*. The student cannot manage more than the practical tasks. The second quote, which is about previous experiences in other laboratory courses, clearly shows the experience of having to rush to get everything done, and lacks focus on learning. Both students experience having lost their overview in attempt to meet requirements instead of focusing on learning. For these students, learning is pushed out of the laboratory, and it is not until they write their report or prepare for the exam that they succeed in linking what they did in the laboratory with the theory.

However, for other students, the time in the laboratory is experienced as an opportunity for reflection. These students experience time in the laboratory as *reflection time*. Here, one of the students describes why it is important to be able to see the link between practical work and theory already when working in the laboratory:

"But obviously it's best to be able to do this [see the link between theory and the practical part] already in the laboratory, when you're in the middle of it and the instructors are there. [...] but when you can see it straight away, then you can already begin to build on it […] and maybe even add more and begin to predict things and be able to say 'well, because we say this now, we might be able to see something over here […] and have already begun to have an understanding that kind of pre-empts things; that you [...] can consolidate your knowledge faster." (D06)

In this quote, the student describes the opportunity to see links, and the importance of using the instructors to verify the understanding the students achieve in the laboratory, and thereby allow them to consolidate a deeper understanding.

Another difference between the two categories is the experience of when and how you learn. Students who experience time in the laboratory as *wasted time* do not associate being in the laboratory with learning. They associate doing calculations or "*studying*" with learning, whereas doing things yourself and being part of all steps in the laboratory process are not associated with learning.

"And there were 9 exercises. That's a lot of time to spend [...] on dealing with a computer rather than sitting and learning something, well, that's what I think." (D05)

"I learn most when I sit on my own and have to figure it out and study for the exam." (D01)

In contrast, students who experience the time in the laboratory as *reflection time* are more focused on the process and how the different parts of the laboratory exercise support a more comprehensive understanding:

"I think it's so much easier when I get to do things myself and try to make... That is, to get a sample started, and then you get the chromatogram... And then have time to look at the chromatogram and learn how to analyse it." (D02)

This student sees the practical work as an opportunity to gain a deeper understanding of the subject matter, in that participating actively in the different steps of the procedures helps them understand the whole picture. This experience indicates that this student has a reflective approach to learning that is holistic and focus on the overall meaning. In this regard, laboratory instruction helps students achieve an understanding of the processes that can be difficult to achieve through other methods, and thereby contributes to sense-making for this group of students.

How feedback and learning support are experienced

Students, who experience time in the laboratory as *reflection time*, also experience that they especially learn through discussions with the instructor or fellow students:

"Because we're in the lab so much, there's a lot of 1-on-1 time with an instructor, and you kind of feel that they've got plenty of time to go over some of the material with you." (D03)

"What [you get the most out of] is probably when you have prepared some data, and then either talk about it with the group or with the instructor." (D06)

The direct contact with the instructor is important – also for the course instructors – but not all students experience that the instructors have sufficient time to review and explain things for them during the laboratory exercise:

*"What I think was missing was maybe a few class sessions or something like that. Where you could take a more in-depth look at things and talk a bit more with the instructors and stuff, because that's what we do in a lot of other courses, but we **didn't** do that in this course... And that's what I think was missing, because if there was something you didn't understand, well, then you could try asking in the lab. [...] but then it was often like, the instructor had to help everyone else in the lab too..." (D01)*

These students want class sessions because they have them in all their other courses, and this is where they usually experience the reflection they feel is lacking in the laboratory and that they feel they need. They experience the time in the laboratory as *wasted time*, because they do not connect the activities they do in the laboratory to learning. Rather, they experience writing reports and studying for the exam as activities that contribute to their learning:

"Well. Yes. Well, there were not any class sessions where you could calculate and do assignments or stuff like that. Well ... it's all so focused on ... it's all just about the exercises." (D05)

How planned teaching activities are experienced

In this course, there is ample time allocated to the exercises. Some students make good use of this time to understand the material:

"[that plenty of time was allocated] meant that you could actually take the time you needed to understand and take the time to not just to find the answer, but also to really understand and, well, learn." (D06)

Some students start writing their reports whilst the instruments are running, or, as is seen in the next quote, swap roles with their lab partner so that both students get an understanding of what the other one is doing. This helps the students learn by having to teach someone else:

"And then we had to set up. And me and my partner had a really good division of work, at least I think so. She was brilliant at Excel ... [so she] got everything up and running and [got] ready to just add the data. I was pretty good at understanding how to [...] program the software, to take the samples in the right order. And the pump rate and stuff like that [...]. And then at some point when you get started, then you swap and you've got a million questions you want to ask, because that's not really what you're good at. But then ... it's like you get a chance to explain. I explain all about the software and stuff. What it means, and it does this, and what that graph means. [...] so you kind of explain to each other the things you know. And that's actually a pretty good

set up. Both because you primarily get to work with what you think is interesting, which makes it more fun and just easier. And because you get to teach someone else the stuff you know." (D03)

However, making sense of the work done in laboratory does not just happen on its own. The students have to actively exploit the time they have in the laboratory to achieve their understanding. When this happens, *reflection time* is achieved. Even though plenty of time has been allocated to the exercise, not all the students succeed at making sense of, and actually understanding, what they are doing. If their experience is that they are in a rush to get the practical part done, the group will often divide the work between them to:

"Finish quickly, or get as much as possible done, even though that means that not everyone gets to try everything." (D04)

Similarly, not all students make use of the wait while the instruments are running to work on their report or reflect on their learning:

"I: What did you do while you were waiting? [...]
Checked up on the next report or just chatted. Not always about academic stuff. [...] sometimes we just lazed about. [...] And if we've, we know we've done something wrong, then we sometimes wait and don't tell anyone that we botched this up [laughter] until there's only half an hour left, because then we don't have to do it again." (D01)

This is an example of a "survival strategy" that students who experience the time in the laboratory as *wasted time* can resort to when they do not experience the scheduled time as meaningful.

How assessment – the exam – is experienced

As mentioned above, in our analysis we focused on the exam. Students who experience the time in the laboratory as *wasted time,* and who fail to make sense of the activities and thus do not achieve a greater understanding, experience a very low degree of cohesion between the work in the laboratory and the exam:

"Because some things were included [in the exam] that had never been there before." (D01)

"It's not until you're at the exam that you realise that you just don't understand. That you really haven't learnt that much." (D05)

"I don't really feel like what we've done in the lab is something that I've been able to really use at the exam." (D05)

In these quotes, the students are most likely referring to those exam questions that test understanding. In contrast to these students, some of the other students thought there was a clear link between the exam and the teaching activities:

"I think there was a good overlap with the exam. I mean, the calculations, the exam and the stuff we'd done when we did the exercises." (D04).

"... and could make links between the exam questions and the stuff we did in the lab and stuff like that. [...] That's where it all really began to fall into place." (D02)

"And that's why it's kind of cool that you can see the same structure [in the exam as in the report]." (D06)

Here, we see the lack of congruence between the teaching-learning activities and the exam that is experienced by the students in the *wasted time* category by the fact that these students are surprised when they see the exam assignments: the exercise activities have not provided them with sufficient understanding on which they can draw in the exam situation. In sharp contrast to this, we have the experiences of the students who felt that they had ample time for reflection in the laboratory. These students can make links to the activities in the laboratory and, at the exam, they actively draw on their experience from the lab.

Furthermore, the students differ with regard to how important they think the exam is:

"I think I've primarily focused on learning as much as I could when I was here, and I didn't really think the exam was that important, well, at least not preparing for it." (D06)

"Well, when I started thinking about the exam, it was mostly about exam questions and practising what to do at the exam, more than about learning as such." (D06)

Students for whom time in the laboratory is *reflection time* understand that the exam is not essential for their learning. These students are more focused on understanding what the exercises are about and on getting the work in the laboratory done, whereas students who feel they are wasting their time in the lab are more focused on the exam.

"I just feel that I learn more from doing some calculations on my own and from doing some exercises that are very relevant for the exam, rather that doing practical stuff all the time." (D05)

"Because I know this is what I will be assessed on and, at the end of the day, it's what counts." (D01)

Already early on in the course, these students think about how they will be assessed and which activities will best help them prepare for the exam. Thus, in their understanding of learning, they award importance to activities that resemble the exam.

Discussion

The results of our analysis show that the students fall into two qualitative categories with regard to how they experience the learning environment in the laboratory depending on (or correlated to) how they experience their time in the laboratory. In the results section, we present the differences in the students' experience compared with the dimensions of congruence in Figure 1. In particular, we focused on the students' experience of congruence between the exam and the laboratory course. We therefore included two dimensions of congruence from Figure 1, *Assessment and feedback* and *Teaching and learning activities.* Assessment is related to the exam and the reports, whereas teaching and learning activities are related to the laboratory exercises and the reports. This is outlined in Figure 4.

The category *reflection time* is represented by the students who feel that they have time to learn in the laboratory. They see a clear link between the practical aspects of laboratory work, data collection, data analysis and the theoretical aspects of writing reports and the final exam. The other category – *wasted time* – is made up of those students who feel that they are wasting their time when working in the laboratory. These students feel that the activities they do in the laboratory are disconnected from the exam. They acknowledge that the data they produce in the laboratory is to be used in the report, but other than that they do not see a strong link between the reports and the activities they do in the laboratory. The students in this category do not see the similarity between the calculations they made in the reports and the calculations in the exam questions to same degree as the students in the other category.

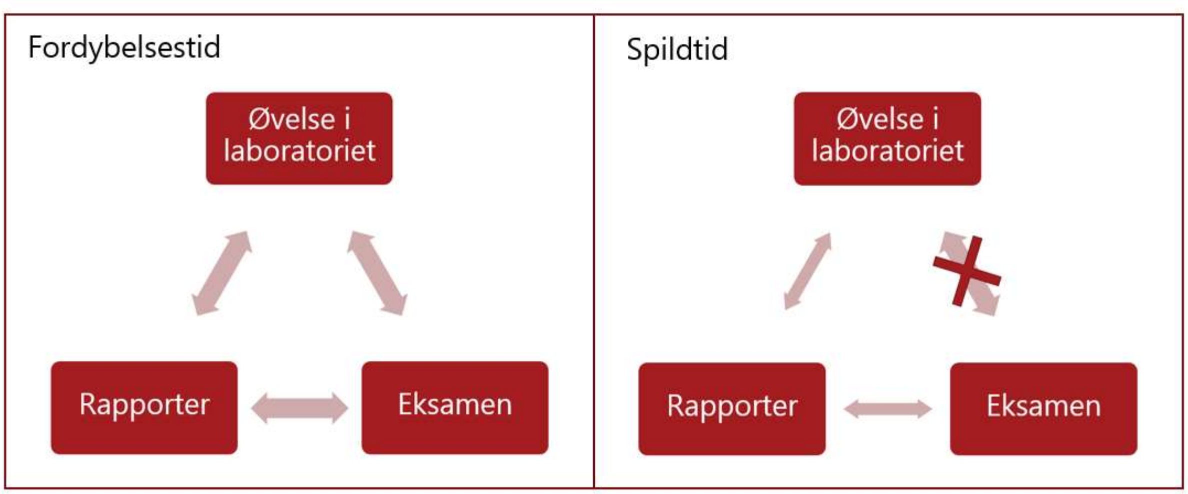

Figure 4 Outline of congruence between activities in laboratory, reports and the exam when time in the laboratory is seen as "reflection time" and as "wasted time". In the category reflection time, *the students experience a high level of congruence between all the course elements. In the category* wasted time, *the students experience no or little congruence between the laboratory exercises and the exam. In the category* wasted time, *the students experience less congruence compared with in the category* reflection time, *because the students do not recognise elements from their reports in the exam situation. The link between the laboratory exercise and the report is also less pronounced in this category.*

Reflection time
Exercise in the lab
Exam
Reports

Wasted time
Exercise in the lab
Exam
Reports

When students experience laboratory instruction as *wasted time*, they miss out on the potential to see the link to the other elements of the course, including the exam. Students who feel that their time in the laboratory is *wasted time* clearly describe using a surface strategy in relation to the activities they do in the laboratory. Ramsden's description of surface strategies is extremely illustrative of how these students experience time in the laboratory: "*They saw the [assignment] as an external imposition – a task to be completed for a reason that was beyond their control"* (Ramsden, 1999). In many cases how the individual student experiences laboratory instruction relies on a number of factors that are not related to the student, see Figure 1. Thus the same student may have a very different approach to and experience of learning in different courses. We see several examples of this in our data. The students feel that the laboratory instruction in the course Pharmaceutical Analytical Chemistry is different from other laboratory courses. This emphasises the complex learning situation the students experience in the laboratory and is in alignment with Hounsell and Hounsell's congruency figure (2007) (Figure 1).

Galloway, Malakpa and Bretz (2016) showed that the way in which students experience control of and responsibility for their own learning contributes to shaping their experiences in the laboratory; our study supports this point. We see that the students' experience of the quality of time also affects how they experience the significance of the laboratory for their learning. Time is a factor that the students sometimes experience they have no control over, particularly if they feel pressured on time or feel that they are wasting their time.

Galloway, Malakpa and Bretz (2016) found that one of the most common goals among students with regard to laboratory instruction was to finish the work quickly. This also applies to the students in this study in the category *wasted time*. Together, two of the perceptions of time identified by Liao et al. (2013), *time as goal* and *wasted time*, match the perception of time in our category *wasted time*. As mentioned above, in a large study of a project-based laboratory course, Burrows et al. (2017) identified eight different categories of time. These categories were not identified in our study; however, we can draw parallels to some of the identified experiences of laboratory instruction. One example of this is Burrows et al.'s *time-saver* perspective, which resembles our category of *wasted time* with regard to the student's objective of wanting to complete their work quickly. Another example is Burrows et al.'s *mastery* perspective, which resembles our *reflection time* category, in that focus is on the students understanding and enhancing their theoretical understanding through work in the laboratory.

Limitations and future studies

In qualitative studies, and especially in a study as small as the present study, it is difficult to assess how common the identified perceptions are. We can say that the different perceptions of time in the laboratory exist, and that the experience of time seems to be a strong indicator of the students' approach to learning. However, it is evident that the study would have benefitted from including more students. Including more students would have enabled us to elaborate on the categories we use, and we might have been able to identify more sub-categories. A more clearly defined focus on the perception of time in the interview guide might have led to a more detailed description of the different perceptions of time. However, *time* was not the original focus of this study, and therefore it was not clearly defined in the interview guide. It is uncertain whether a larger study would have enabled us to identify just as many categories of time as Liao et al. (2013) were able to in their study that identifies the six different categories, as Liao's study is not limited to laboratory instruction. Having said that, we do not feel convinced that the many categories of time perspective are relevant nor that they would bring more insight.

We have previously seen that qualitative phenomenographic studies have led to quantitative studies that have then determined the prominence of the different perceptions. It would be interesting to conduct such a quantitative study in the future. The decision to change the design of a course is a difficult one to make because implementing change is complex and time consuming. Seen in this light, a quantitative overview of how common the perceptions we have identified could be informative. This could be followed up by a qualitative study (similar to the present study) that could provide more knowledge about how to prevent some of the issues that students face.

Practical and pedagogical implications

Even though *some* students may feel it is a waste of time to learn specific skills such as how to use instruments through computer software or how to perform analyses following set instructions when these skills are not assessed directly at the exam, this does not mean that there is no link between the exam and activities in the lab. And some students – as we have also seen in this study – report that they appreciate what they have learnt from doing practical work in the lab, and that they draw on this knowledge and experience in the exam situation. Thus, making the link between the work in the laboratory and the exam more clear could help those students who fail to see this connection.

When planning the lessons, the instructors could consider whether it is possible to adapt the exam to enhance the links to the laboratory activities. Alternatively, new ways of assessing the practical part of the course could be introduced, in which links to the work in the laboratory is made more clear to the students.

In addition to re-thinking the way students are assessed and to making the link between activities in the laboratory and the course aims more clear, the majority of the students will most likely improve their learning if they are supported in developing their (own) learning methods. The challenge is to do this in a way that takes the different needs and personal preferences of students into consideration. One approach could be to adapt the teaching activities so that it is made more clear to the students how they can best use the time in the lab. This could be done by ensuring the students have a more clear idea of what they will be doing in the lab and why they will be doing it, at the beginning of the course. One way of doing this could be to set up relevant *pre-lab* activities in which the students prepare flow charts either in groups or individually that can enhance their understanding of the function of the laboratory activities (Grosskinsky, 2019).

Galloway, Malakpa and Bretz (2016) discuss that, even when students receive the same instruction, they may have very different responses to their experiences. This is why it can be challenging for the instructor to know how to help the students understand what they can gain from the activities in the laboratory. One way of achieving this could be to follow the lead of those students who do in fact succeed in making sense of the laboratory activities, for example by switching roles with their lab partner and asking each other questions, just as we saw one of the students in our study do. In the laboratory course that is the focus of this study, extra time (and space) has been allotted to laboratory activities (Figure 2). Therefore, the students might benefit from the instructor being more clear about how the students are expected to use their time, and from the instructor using different tools to optimise the time spent in the laboratory. In our opinion, it will not necessarily help the students if they are required to prepare or work in a specific way; doing so may in fact have the opposite effect, namely that the students do what they are asked to do without further reflection.

Conclusion

The present study shows that the way in which students experience the scheduled time in the laboratory is closely related to the way in which they experience the outcomes and the relevance of the laboratory instruction. We see that the students have two qualitatively different experiences of their time in the laboratory: they experience it as either *wasted time* or *reflection time*. The way in which the students experience time greatly affects their experience of congruence between the laboratory instruction and the examination. When the students feel that they are wasting their time in the laboratory, they struggle to see the link between the laboratory course and the exam. In contrast, when the students experience their time in the laboratory as *reflection time*, they also experience a stronger link between the laboratory course and the exam. In our study, we found a correlation between how time is experienced and how students approach learning. Students who experience time in the laboratory as *wasted time* are more likely to make use of surface strategies. When we compare our results with similar studies or with studies of the experience of time, it appears that including more interviewees would allow inclusion of more nuances than are included in this study, which is limited by being based on six interviews. We suggest that laboratory course instructors reconsider how practical activities are assessed, so that activities in the laboratory are not seen as being isolated from the rest of the course. In addition, we suggest that more attention be given to how the instructor can increase the students' reflection on their own learning.

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Appendix 3 : Paper 3 – When the Lab Work Disappears: Students' Perception of Laboratory Teaching for Quality Learning

JOURNAL OF CHEMICAL EDUCATION

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When the Lab Work Disappears: Students' Perception of Laboratory Teaching for Quality Learning

Published as part of the Journal of Chemical Education virtual special issue "Teaching Changes and Insights Gained in the Time after COVID-19".

Laura Teinholt Finne,* Bente Gammelgaard, and Frederik Voetmann Christiansen

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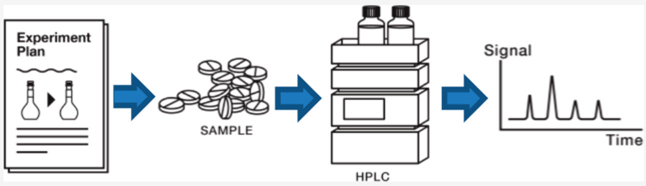
ABSTRACT: During the spring of 2020, teaching laboratories worldwide were closed, and teachers quickly prepared online substitute activities. This study investigates the students' experience of the substitution of laboratory teaching with theoretical activities in an instrumental analytical chemistry course in the students' second year of study. Twelve students were interviewed about their experience of the online teaching activities and their perspectives on what happens to their learning experience when the laboratory disappears and is replaced with theoretical online activities. Interviews were conducted 2−3 weeks after the lockdown of the teaching laboratories. Transcripts were analyzed with inductive interpretative thematic analysis with a focus on students' conceptions of the role of laboratory teaching in quality learning. The results show that the laboratory experience and the close connection to teachers in the laboratory setting plays an important role for the scaffolding of students' learning through dialogue and feedback. The analysis is informed by the description of the laboratory as a site for text production. It shows the role of the teaching laboratory in shaping embodied understanding of the scientific knowledge production process through series of transformations.



KEYWORDS: *Chemical Education Research, Second-Year Undergraduate, Hands-On Learning/Manipulatives*

FEATURE: Chemical Education Research

INTRODUCTION

Since the 19th century, laboratory teaching has been a part of the university science curriculum. Experimentation is a central part of science, and therefore, many consider it self-evident that engaging in laboratory work should be a part of science education.[1] However, it is important to distinguish between doing science and teaching science. Evidence for the quality of teaching and learning in the laboratory is ambiguous.[2,3] The reported learning outcomes from laboratory experiences are multimodal and manifold, as are the stated aims of laboratory teaching and learning.[3,4] Broadly, laboratory teaching at the university level is conceived to contribute to developing students' subject learning as well as providing students with practical skills, scientific skills, and general skills, but these potentials are not realized automatically.[4] Some studies show that students in laboratory courses did not perform any better on examinations than students who did not participate in laboratory courses,[5] and clarity of goals and appropriate assessment formats seem to be a condition for realizing the potential. Much research on the outcomes of laboratory work has focused on secondary education, and at the university level, the focus has been on teachers' goals for laboratory teaching[6] and not on the actual student outcomes.

In a recent systematic literature review[7] on students' learning outcomes from university laboratory courses in the chemical sciences, the multidimensional and diverse learning outcomes are confirmed also for university teaching. The analysis of empirical research studies generated evidence for five clusters of learning outcomes including experimental competences, disciplinary learning, higher-order thinking, transversal competences, and affective outcomes. However, the problem with this multidimensionality is that the aims of laboratory courses are conceived differently by different teachers, and this leads to confusion and misalignment between students' expectations and faculty goals.[8] Further, laboratory exercises are not always well-designed; often, they are packed with exercises and become for the students a "hands-on" activity without the necessary time for "minds-on" reflection. Laboratory courses are expensive compared to many other teaching formats such as lectures or classroom teaching. To legitimize the amount of staff-hours,

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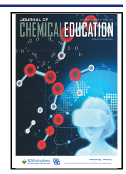

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chemicals, equipment, and space needed for laboratory teaching, the authors call for more evidence for the importance of laboratory courses.[1,9]

In the spring of 2020, a rather unwelcome opportunity presented itself as COVID-19 closed the universities. At the time, we were engaged in a longitudinal study of students' conceptions and approaches to laboratory teaching, and for the remainder of the semester, all teaching, including laboratory teaching, was changed to online formats.

The students we followed in our longitudinal study participated in an analytical chemistry course. The data previously produced in the laboratory by the students themselves was now replaced by data delivered by the teachers via the learning management system (LMS). At the time of lockdown, the students had participated in about half of the course and had gained familiarity with the laboratory.

The unusual situation opened an unexpected opportunity to expand our study with additional interviews with students on how they experienced the difference between learning from laboratory teaching and a teaching format where the laboratory experience was missing. Thus, our interest in students' conceptions of and approaches to laboratory work could now be supplemented with students' perspectives on the contrast experienced between doing laboratory work and working with the subject matter in "dry" settings, and students would be able to elaborate on their perspectives on the role played by laboratory work for their learning.

■ RESEARCH QUESTIONS

The aim of this study is to explore the students' experience of the change from laboratory teaching to online theoretical teaching with respect to the origin of data, data handling, report writing, and feedback. We are interested in how the students experienced the change from onsite laboratory teaching activities to online teaching activities and what this can tell us about the students' perceptions of the teaching laboratory. Thus, we want to answer the following research questions:

- How do students experience the replacement of laboratory teaching with theoretical teaching?
- How can these experiences shed light on the role of laboratory teaching in the students' perception of quality learning?

■ THEORETICAL FRAMEWORK

The present study was highly explorative in nature, and we sought to understand the student's experiences. From our analysis, we found that the laboratory is important for the students in two ways. It provides, on one hand, students with an epistemological perspective on how knowledge is created as part of a scientific work process and, on the other, a pedagogical perspective related to how their understanding develops and is supported in the process through feedback from the teachers. To theorize our understanding of the epistemological importance, we have based our analysis on a description of *the research laboratory as a place for text production and transformation of texts* as described below. Further, to understand the pedagogical importance, we have built our analysis on theories of feedback and scaffolding.

Laboratory as a Place for Text Production for Explanation and Deeper Understanding

The sociologists of science Latour and Woolgar[10] have provided a thoughtful anthropological account of the workings of a research laboratory. They describe how researchers alternate between laboratory workbench and literature studies in the offices and how material samples brought into the laboratory undergo transformations and are represented in different ways as part of the experimental process, aided by the use of measurement apparatus and technological tools. The data the scientists are considering stem from operations such as assays, reactions, and different measurements. These are manipulated further by the scientists to demonstrate relations to theoretical models, literature findings, etc. The data output from measurement devices is described by Latour and Woolgar as *literary inscriptions* and takes the form of numerical or graphical outputs, e.g., data points, peaks, marks, and numbers. The instruments producing the literary inscriptions are referred to as *inscription devices*. Thus, they describe the laboratory as a site of *text production* in which a *series of transformations of texts* take place. The texts produced in the laboratory comprise a broad group of representations of phenomena such as pictures, numbers, tables, figures, graphs, and prose texts. Together, the series of texts produced in the laboratory provide support for the comprehensive arguments in the journal articles that the scientists produce. In order for the arguments in these articles to be convincing, the literary inscriptions and interpretations of these must reflect somehow the phenomenon under scrutiny. Thus, when a literary inscription is produced, it retains, at least in the minds of the scientists, a strong causal link to and significance of the sample under scrutiny.

We have transposed Latour and Woolgar's description of a research laboratory as a site of text production and transformation of texts to the teaching laboratory. In both cases, the production and transformations of texts are supported by inscription devices and literary inscriptions. Like the scientists in the research laboratory, the students in the teaching laboratory are involved in similar series of transformations of "texts", while maintaining the "causal connection" to the phenomenon studied. Obviously, their resulting work is not presented to anonymous peer-reviewers in a journal, but their reports are also presented for assessment to experts: their teachers.

Feedback and Scaffolding

The laboratory is a special learning environment where there is much potential for formative feedback to the students. For formative feedback to be of high quality, the *timeliness* of formative feedback is considered to be of great importance.[11] When the feedback is not timely, it interrupts the workflow, becomes time-consuming, and may be conceived as irrelevant. Further, timely feedback and elaboration on the answers are important. Providing the students only with knowledge of the answer being correct or incorrect can lead to demotivation; rather, elaborating on the answers is important in providing formative feedback.[12,13] Time to engage in dialogue is important, as dialogue is important to support effective formative feedback.[14] The interaction that occurs in a dialogue plays an important role in scaffolding the students' learning.[15] Scaffolding can be described as the help and guidance necessary for learning. Scaffolding is closely related to the theory of the zone for proximal development introduced by Lev Vygotsky.[16] If the comfort zone, representing the already acquired knowledge and skills, is seen as the center of three concentric circles, the second circle is the zone for proximal development, and the third circle represents a zone out of reach for the learning. To learn, the student must move from the comfort zone into the zone of proximal development. Hence, scaffolding is used to describe

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instructional techniques teachers or peers apply to help students to move into the zone for proximal development and thereby achieve a stronger understanding and a greater independence in the learning process.[17] When the students do not understand the given feedback or do not receive the proper help or guidance, they are not reaching their full learning potential.[18] Proper scaffolding demands that the teacher understands the gap between the students' present and expected level of knowledge/competence.[19]

■ CONTEXT OF STUDY

The curriculum of the Pharmacy education at University of Copenhagen (UCPH) includes several laboratory courses in the bachelor education; about a third of the students' scheduled activities is laboratory teaching. The study object is a course in Pharmaceutical Analytical Chemistry which is followed by the students in their second year. The course focuses on drug analysis based on instrumental methods. Details on the course are presented in Box 1. In the laboratory setting, two classes of approximately 25 students are present at the same time, and each class is followed by a teacher. At least one of the two teachers present is an experienced associate professor. During the laboratory exercises, the students have ample time for preparing, reporting, and answering study questions for the reports. Thus, next to the work benches are study tables where students can work in groups on analysis of their findings, study questions, etc. The teachers are available for help with practicalities, answering questions, and discussion. Corrected reports from previous exercises are handed back in the laboratory, and oral feedback is given concerning students' answers; discussions can be initiated either by students or the teacher. In the online format during lockdown, students wrote their reports in groups, based on data from the exercises provided by the teachers on the LMS. Extra explanatory material in video format was provided, explaining how the data should be understood. Students handed in the reports by email, and teachers returned the reports with written feedback as comments (and/or proposals on where to find theoretical explanations) in the document.

Box 1. Description of the Course Pharmaceutical Analytical Chemistry

Placement: fourth semester compulsory course (approximately 200 students in 8 classes)

Scope: 7,5 ECTS (European Credit Transfer System)

Format: 19 lectures, 72 h of laboratory work (16 × 4 h sessions in groups of 2−3)

Assessment: 3 h written exam, laboratory work is marked passed or not passed based on 8 reports

Course material: English textbook, Danish laboratory instructions, Danish summary of core content. Available on learning management system (LMS): lecture videos, lecture slides, compulsory quizzes, and report schemes (for recording measurements, study questions etc.)

Analytical methods worked with in the course: Liquid chromatography (HPLC), gas chromatography, UV−vis spectrophotometric detection, mass spectrometry

Content: Analytical principles, quantitative determinations, validation, data analysis, critical assessment of results, plan experiment from pharmacopoeia monography/standard

Central learning objectives for the course: Choosing appropriate methods of analysis for pharmaceutical problem and conducting experimental analysis using appropriate calibration method. Adjusting experimental conditions and validating method employed. Critical data treatment and precise reporting.

■ DATA AND ANALYSIS

Twelve students were interviewed online in Microsoft Teams during April 2020. The students had experienced ordinary teaching from the beginning of February until the lockdown in mid-March. The focus of the interviews was the students' experience of the online teaching situation compared to the regular teaching in the laboratory they had experienced. All students had given informed consent to participating according to the GDPR (General Data Protection Regulation) rules of UCPH. Prior to the interview, students filled in a short survey to inform the interviewer about their progress in the course and whether they had received feedback on the reports. The interviews were semistructured[20] and focused on the following themes: preparation for lab, support, group-work, feedback on reports, experience of learning outcomes, and experienced variation in their everyday life. Survey questions and interview guide are provided in the Supporting Information.

The interviews were recorded, transcribed, and then coded using inductive interpretative thematic analysis.[21] The first step was to familiarize ourselves with the data; after reading the transcripts, initial themes were determined between the authors. The first author then coded all transcripts after these codes. To secure agreement between the authors, the codes were discussed among the authors after reconsulting the transcripts. This discussion led to a redefinition of three overarching themes followed by a recoding of the transcripts into these themes by the first author. One theme was concerned with the general experience of the lockdown and is not reported here. Two overall important themes were discerned: "contact to the teacher" and "when lab is missing". Compared to the previous interviews we had conducted, it was striking how similar the students' experiences of the change in teaching mode were and how they were overall in agreement about the detrimental effect on their learning experience. Hence, our focus in the analysis was to elucidate general experiences caused by the change in teaching format (as a result of the laboratory closing) and the variety within the overall themes considered. With our research questions in mind and through several iterations of analysis and refining, we arrived at the resulting themes. All interviews were conducted in Danish, so the quotes presented are translated from Danish. The translations have focused on providing an accurate rendering of conceptual meaning expressed in the interviews. Further, the translations have been discussed among the authors in relation to the full interviews until consensus on the English wording was reached.

■ RESULTS

The students generally expressed a feeling of missing out on something when they were not in the laboratory and did the experiments themselves. The importance ascribed to the laboratory teaching falls in two categories which we describe as *pedagogical* and *epistemic importance*, respectively. In the following presentation and analysis, we present quotes from the interviews followed by analysis.

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Pedagogical Importance of Laboratory Activities for Learning: The Quantity and Quality of Feedback

The students describe that the close and informal contact with the teachers is lost in the online teaching activities, because the teachers were less available for questions, feedback, and discussions compared to the face-to-face laboratory teaching activities, where they are available for questions and guidance throughout the day. Assistance for progress in the report writing was not available when needed, and the barrier for seeking help was perceived as challenging. The experienced barrier concerned not only the *accessibility* of the help but also the conceptual *difficulty* of *asking the proper questions*. While the instruments are producing data in the lab, students have time to start their report writing, and to answer the "study questions" in the report scheme, and teachers are accessible for help. When changing the laboratory teaching to online theoretical activities, communication with the teacher become delayed and asynchronous. The experience is described by these students:

> *"[...] when you are in the lab you can just ask [the teacher] right away and then you get an answer right away. But when you write an email and then maybe get an answer a couple of hours later, or the next day, then maybe you have forgotten... When you are in the situation, you have a clear sense of what you don't understand—but when you read it again the day after, then you have to understand it anew, and then it takes a long time, right?" (D07)*
>
> *"But it is as if you don't get the help in the same way, because it is just not as accessible." (D05)*

When the help is delayed, the *quantity* of feedback provided to the students decreases because of the limited accessibility of the teacher, not least because the students are not seeking the feedback to the same degree. The first quoted student expresses frustration related to the delayed response from the teacher highlighting the importance of *timeliness*.

The second aspect of the experienced barrier for getting help is concerned with the students' *ability to formulate questions*. This is described by this student:

> *"I think everyone in the group feels that it is harder to make the effort to write to a supervisor. You really feel you have to phrase it right and really know exactly what it is you want to ask. [...] I don't know many who'd like to do that, compared to when you're in the lab where you'd just ask. In the lab I feel it is much more normal just to go and ask [the teacher]." (D09)*

In the teaching laboratory, communication between teacher and students occurs also through body language and gestures used to designate what one does not understand. Thus, it is not necessary to ask eloquently formulated questions. The student might simply point to something and have the teacher elaborate on what is being seen. In the ensuing discussion, the teacher can help to formulate the question. In the online teaching environment, the students are deprived of this help in formulating questions, and this may keep students from asking questions that they would have raised in the laboratory setting. This may also keep students from following up on the written feedback they received on the reports:

> *"Obviously we can always write back [to the teacher] and ask questions but you just don't do it because perhaps you don't know which questions to ask, if your report it just "passed". But it is a pity that you don't get more elaborate feedback on your work." (D09)*

The student here describes that feedback from the teacher may be available, but the possibility is not used. This also touches upon the quality of the feedback. The students experience that the formative feedback on their reports is not sufficiently elaborated in the online format. When teachers give back the corrected reports in the laboratory, written feedback can be supplemented by a discussion of the students' answers and the rationale behind and students have the opportunity to ask questions, regardless of the pass or fail status of the report. In the online format, the students get primarily summative feedback, supplemented with correct answers or references to theory. If the report is marked passed, the students do not follow up on the comments the teacher has written and hence do not go into details of their answers.

This student describes the process of the feedback situation in the laboratory setting:

> *"There were some specific questions [the teacher] had selected, that we talked about and [the teacher] asked what we thought and what else you could have done and so on. So, you got to talk about it instead of just writing it down. It gives you a better understanding of the subject to put your thoughts into words, or at least I think so. And also to unfold the thoughts behind the answers we have given. And then the discussion goes back and forth until [the teacher] [...] was sure that we had a good understanding of it. And then [the report] is accepted in the end. But I feel we had more of a dialogue about it." (D09)*

The students and the teacher discuss unclear points and elaborate together on the answers given in the report. This enables the teacher to catch possible misconceptions and help the students along. This dialogue with the teacher is highly valued by the students. The students are very conscious about the elaboration they get on their answers in the laboratory. Further, the teacher's questions promote the students' learning through the discussion:

> *"[in the lab] there is no distance between you and the teacher and there is not the same. . . When you have a dialogue about something you often start wondering... [...] There's not a dialogue in the same way now. Maybe you realize: "Wow! I had understood this in a different way or [...] the teacher [...] elaborates on something which makes you... that I can... which makes me think of other things or connect pieces... I might relate it to another exercise or... you know... It just sparks [...] your reflections and thoughts and experiences in general." (D15)*

Dialogue is seen here as an important means to support effective formative feedback. The student points to the fact that the dialogue sparks reflections and connects new concepts to earlier experiences. The interaction is scaffolding the student's learning. In the online format, the process of scaffolding is much more difficult, because the dialogue intended to scaffold the learning process is missing. Here a student describes the scaffolding process that happens in the laboratory and the lack thereof in the online format:

> *"In particular, when your supervisor confirms what you've done, or if you... when you pose a question and [the teacher] says 'Yes, sure, that seems...' and 'it is fine results, it looks good' and so on. So, you are confirmed that you are on the right track and this is not the same when you are at home. Then you have to judge yourself whether you are totally off-track or not, right?" (D07)*

The small hints, confirmations, and encouragements from the teachers help the students stay in the zone of proximal development. When deprived of the dialogue, the students

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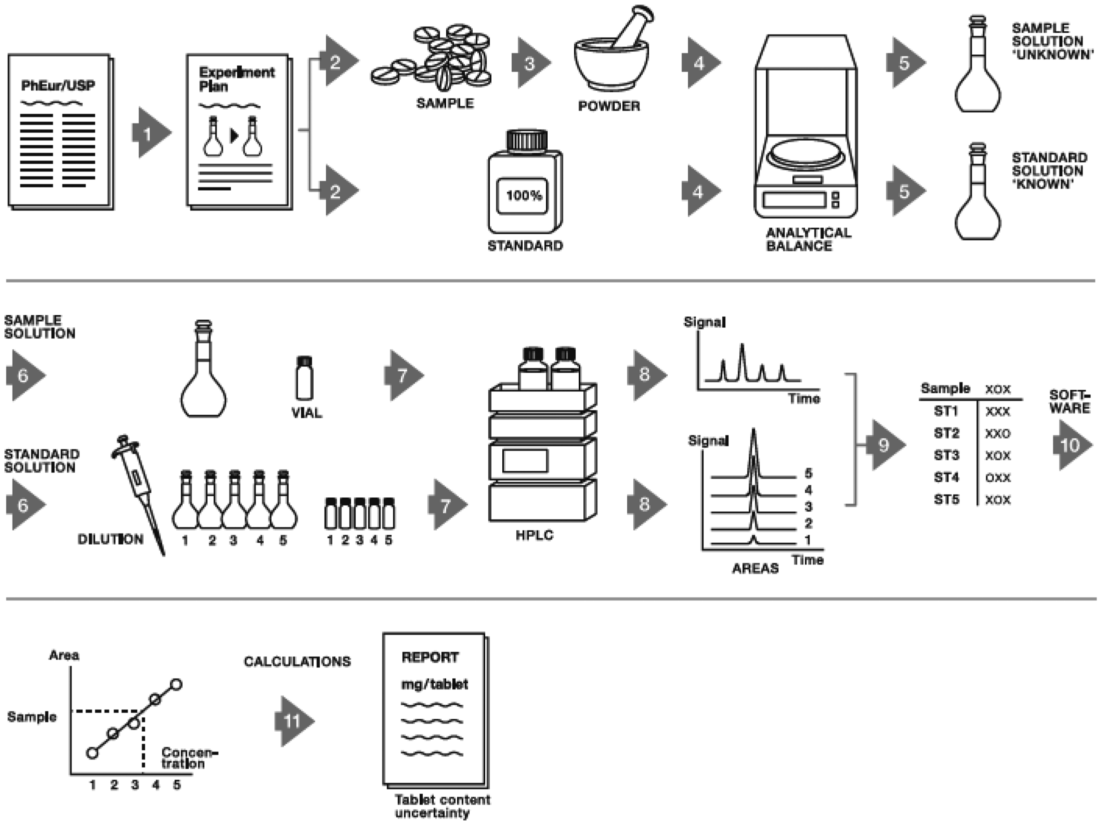

Figure 1. Transformations occurring during a laboratory exercise with the purpose of controlling the content of drug substance in commercially available tablets. The exercise encompasses all steps from interpreting the pharmacopoeia, planning the experiment, preparing samples, performing HPLC analysis and data analysis, and finally interpreting the results. The transformations are represented by numbered arrows. Some transformations involve inscription devices producing literary inscriptions (e.g., 5 and 8). Other transformations require interpretation (1), physical handling (6), or calculations (10, 11).

express giving up more easily or spending unnecessarily long time on small details.

Epistemic Importance: The Role of the Laboratory in Establishing Structure for Understanding

We used the theoretical framework of transformations in the research lab described by Latour and Woolgar[10] to describe and understand the teaching laboratory. To briefly summarize, they describe the laboratory as a place for *text production*, where *inscription devices* produce *literary inscriptions* that scientists interpret and compose into scientific arguments for the scientific community. An example of the series of transformations in a laboratory task is given in Figure 1, based here on one of the actual exercises in the analytical chemistry course under scrutiny. While the students in our study obviously do not use the terms of literary inscription and inscription devises suggested by Latour and Woolgar, it is clear from the interviews that the gradual textual transformation of findings at play in the laboratory setting is a crucial element of their learning experience in the laboratory, and something which they find is absent in the online activities that followed the lockdown.

Figure 1 describes examples of transformations occurring in the laboratory setting (e.g., transformation from tablet to measurable product, from product to measurement output, etc.). In the subsequent online teaching, all the steps (1−8) leading to the literary inscription (the chromatogram) are bypassed. The students struggle to understand the absent transformations. This student explains how the focus changes and how the difficult parts of the exercises are conceived differently in the laboratory setting compared to the online setting:

> *"I think that in the lab what you spend most time on... [for instance] we had to prepare some solutions. Which ones should we be measuring on? Not so much on the data that comes out of it.—Because that has been easy. You could see that afterwards: 'Ah, ok, there was a step before this, which was the hard one.' Whereas now the hard part is to understand what "this data thing" is in the first place" (D15)*

The relationship between phenomenon and ensuing data is clearer in the laboratory, and it is easier to understand the origin of the data compared to when data was just provided. Also, the considerations of the practical aspects were completely absent in the online activities. This hinders the student's understanding of the content, as described by this student:

> *"I think it is because you don't understand the chemical concepts in the same way [...] You don't have the same kind of understanding of what happened, what it is you are measuring and you... you just spend a lot of time trying to understand what is going on". (D05)*

Performing the experiments themselves enables the students to engage in and comprehend the transformations of texts in the laboratory and thereby see the connections and understand the causal relationship between the phenomenon, experiment, and data. In the online setting, despite the instructional videos, the process of building an argument based on knowledge of the origin of the data becomes much harder.

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Embodied Structure. In relation to the description of transformations in the laboratory as described above, we found that the students experienced that the presence in the laboratory provided them with an embodied structure. The students described the importance of being physically present in the specialized environment of the laboratory, with all of their senses at work. The embodiment experienced by the students is related to the *physical* embodiment described by Kersting and collegues.[22] Two students describe the role of being physically present in the laboratory vs. the online situation in the following ways:

"It think it is just that you did not have that visual aspect and that part where you actually have your hands-on. Your body has not been engaged in the same way as when we are in the laboratory [...] ...then you also remember the experiences you had down there. I think it is something different just to sit down and write an assignment" (D09)

"It is difficult to separate because there is no... what can you say... impressions or experiences that I can relate it to." (D15)

It appears that the experience is important for the students in providing an embodied structure to their learning experiences.[23,24] It also helps the students to distinguish between the different exercises:

"It is like... you cannot really handle it when you do not try it yourself... and experience 'oh yeah... now I see... if you raise the temperature then this happens' and... well... knowing how sensitive the way you inject is" (D02)

Across the interviews it seems clear that the embodied laboratory activities have a crucial role in providing *structure* in the students' understanding. However, there are different ways in which embodiment provides structure to the students' learning process. In the following, we will distinguish between three different ways in which the bodily experience can help structure the students' meaning making process: temporal, narrative, and causal structure. We illustrate them by quotes from the students.

Embodiment may provide *temporal structure* to the learning process. The temporal structure provides a direction of time in the laboratory experience. In the online setting, the students experienced that the *laboratory process* disappears and that the temporal aspect was somehow reversed:

"But when we are not doing it and we only deal with it theoretically [e.g., being online], then maybe it is not so important if you understand exactly how the process works. [...] You just solve the problems that are related; you don't have to perform it. [...] I think the whole laboratory process is missing, where you end up with your own data and you understand... ok, that's why the graph looks as it does. Because you start... What I really like about the lab is that you start from the beginning and then build it up and you end up with some final result. While here you get the final result and then you have to work backwards and find out: Ok, how did that happen?" (D06)

While being able to "work backwards" is certainly a relevant competence to achieve, it is considerably more complicated to do, and the overview of the laboratory process from beginning to end is lost. The student expresses the need of this overview for understanding why and how the data appeared.

The embodiment may also provide a *narrative structure*, a kind of storyline that connects the theory and practice and in which the students play an active role. A narrative structure may help the students distinguish the purposes of different exercises from each other and make valuable connections between theory and practice. When students do not experience laboratory exercises, they can miss the "plot" of the exercise altogether, as described by this student:

"It is a bit vague what we really knew... For instance, the one [exercise] where we quantified vitamins in vitamin pills—we didn't even know that was what we did! That it was vitamin pills! So, you don't really get the essence of it. You might understand the theory but the point of the exercise... no one... we didn't understand it." (D07)

This is a clear example of the theory and practice disconnecting as the laboratory disappeared. When the students produce the data themselves after dissolving the tablets, they hold the glass of vitamins in the hand, and the purpose of the exercise to quantify the content of vitamins in the tablets becomes obvious. The students express a feeling of deeper connection to the data when they have adjusted the instruments themselves and observed the transformations and procedural steps in the production of the literary inscriptions and the ensuing transformations.

Importantly, the embodied experience may also provide a *causal structure* when students are involved in the manipulation of apparatus and observe the effects of their manipulations. When students are provided with data to analyze rather than produce the data for analysis themselves, the whole series of transformations that go before are missing:

"When you sit there, with a given data set, then it is not certain that you understand why it looks like that or what they did to arrive at that." (D07)

"Then you have to figure out [...] Where do the numbers come from? Which process has the whole thing gone through. When you haven't done it yourself it is just... firstly, it is somewhat harder to understand because you haven't done it yourself and it is also more difficult to remember." (D05)

Thus, the students have to imagine through which processes and transformations the data were produced. Also, even if they succeed in figuring out and understanding the connections, they experience the understanding gained as of a more superficial and shallow level. This contrasts with the laboratory situation where the student is experiencing the causal effects firsthand:

"It is when you have to do the settings yourself and see what actually comes out of it and what happens. That just gives you a much better understanding than just being told how things are proceeding." (D09)

When working only theoretically, the data and the phenomenon may become detached from each other, and the causal connection between data and phenomenon may disappear. One student describes how analyzing handed-out data resembles a meaningless game, when the entire exercise was meant for performing it themselves:

"Well... I think that what we are doing now; it is like we're playing. We pretend that it happened, or theoretically it happened, whereas when we have been in the lab then it is something that actually happened and actually can happen! Then it is not just something that can happen hypothetically or we think, that is what happened. Then we more or less know if it is true." (D10)

When the students do not engage in and observe the experiments themselves, they lose the sense that the data represents something real; the data comes across as "model data" rather than as "actual data" that they themselves had a hand in producing. The students are not as such questioning

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whether the data is/are real, but not having been active in production of the data changes their conception of the relevance and status of the data:

"I am well aware that it is real data, but I think the understanding and overview of what you are doing is being lost a little." (D10)

The interviews show that the students prefer to produce the data themselves. Not because they think the data becomes better, but because engaging in all the transformations the data undergo in the laboratory process gives more of an ownership of the findings. It also helps them in the process of identifying problems and mistakes compared to the theoretical situation:

"It's a bit more difficult to understand what the data is and if some things are not quite right then it is difficult to figure out where the mistake is because you haven't done it yourself. I would definitely prefer to do produce the data myself compared to just getting it because I think it's more difficult to get an overview. Before you start you spend much time on where data originates, what part belongs to what, and what the data means." (D09)

Laboratory experience is important for developing the students' epistemic knowledge about the complex relationships between the phenomenon, experiment, model, and data. The students experienced that the embodied experiences in the laboratory provided them with important ways of acquiring knowledge and understanding how experimental knowledge comes about. The interviews also indicate that the physical interaction with the inscription devices and the phenomena in the laboratory promoted their understanding of the epistemic status of the literary inscriptions produced by the devices and the relationship between the textual inscriptions and the phenomenon studied.

■ DISCUSSION AND IMPLICATIONS

A central finding has been the importance of feedback from teachers in the laboratory setting. Adequate time for formative feedback allows for timely feedback, and in this course, there was ample time for students to engage in dialogue with the teachers in the laboratory setting. Shute[14] points out that effective and useful formative feedback depends on motive (perceived need), opportunity (timeliness), and means (willingness to use the feedback). According to the students' description of their experience, all these points were fulfilled in the laboratory setting, but not in the online environment that followed the lockdown. Working online, the students lacked primarily the opportunity, and when the opportunity finally arrived, the students had often lost the motive or the means.

As for the epistemic importance of the laboratory learning experience, our results indicate that being in on the entire process of creating knowledge through transformations is a central outcome of laboratory learning for the students. We have seen that "being there" physically through the consecutive steps of the laboratory process was conceived as important for the students.

In the analysis, we have applied the perspective of Latour and Woolgar[21] describing a research laboratory and have argued that the basic ideas can also be applied to the teaching laboratory. The description of the transformations of materials and representations happening in the laboratory are of central importance and occur in both types of laboratories. To be sure, students in the teaching laboratory are not as familiar with the laboratory and the instruments as researchers. They are still in the process of understanding the function of the inscription devices and the scientific concepts involved. Hence, the students work with established procedures and more straightforward experiments compared to the more explorative research experiments, at least in most undergraduate laboratory courses like the one considered here. Still, students in the undergraduate teaching laboratory can be said to mimic aspects of the *laboratory processes* also taking place in research laboratories. They observe, engage in, and follow the samples into literary inscriptions and subsequent transformations, and they discuss their findings at the various steps of the process. Thus, the experience of operating the instruments and engaging in the transformations of data is an important part of the learning and understanding the causality of experiments and the role played by experiment in scientific processes.

So far, we have considered the pedagogical and epistemic importance of laboratory teaching as two separate themes. However, the two themes could also be seen as two sides of the same coin. The day-to-day scaffolding of the students' learning in the laboratory through dialogue with instructors is a key feature of most laboratory work, and indeed, it may be something of a necessity in order for students to successfully maneuver in the complex learning environment. Indeed, scaffolding is also a prerequisite for the students' learning about how knowledge is established through experimental work. The dialogue, feedback, and prompts from the teacher, formal as well as informal, are important for the students' experience of developing scientific judgment, that is, the students' ability to evaluate the validity of their own and others' results. This also includes identification of errors and gaining experience with practical complications or strange results due to errors or mistakes either made by themselves or the instruments. Making a "good report" is not just about getting the right results according to some scientific standard (assessed by the teacher). It is also, and crucially, about understanding the various steps involved in the process, so you may trust the results you have obtained through the series of transformations occurring in the laboratory process. Indeed, it is very often in the transformation of representations that students need help from the teachers and fellow students, to make sure that they are interpreting or presenting results in an adequate and acceptable manner. It is about teachers and students trusting the results obtained and interpretations made, and about agreeing on how the findings can be described. From this perspective, the feedback is not just a pedagogical tool or a question of pedagogy but is also about conveying to students how experimental knowledge is and should be established and validated; it is about intersubjectivity and transparency of experimental results. Key findings and implications of this study are found in Table 1.

■ LIMITATIONS

As the Pharmacy students spend many hours in the laboratory, it is not surprising that they experienced missing out on something when the teaching laboratories closed. Moreover, the abrupt change in the students' study routines caused by the lockdown was obviously generally conceived as unwelcome by the students. The change was just as abrupt for the teachers who had to reorganize the course on a very short notice; given more time to prepare, the teachers could (no doubt) have afforded a more fruitful online learning experience than what could be accomplished in the overnight change that had to follow the lockdown. This is also why our focus was the students' conceptions of quality in relation to the laboratory work they experienced, and not on the online experience. Furthermore, as

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Table 1. Summary of Key Findings and Implications

Key Findings[a]	Implications[b]
Elaborate and timely feedback	Plan face-to-face feedback sessions and more time for experiments
Contact and dialogue with teacher	Importance of TA's or teacher's role in scaffolding students' scientific judgment, staff and TA education
Experience of transformations of materials and representation	Students should participate in all aspects of experimental procedures
Embodied structure	Difficult to gain embodied structure from online activities, students need access to laboratories

[a]Central characteristics of learning in the physical laboratory. [b]Factors to consider when planning physical laboratory work.

our recruitment took place via a lecture with only around half of the students present, we recognize a certain sample bias. The type of students that volunteer to be interviewed may not be representative which also restricts the diversity of our sample. No data on the students' academic performance or attitudes was collected, so it is not possible to determine if the recruited students are representative.

CONCLUSION

Our study shows that the laboratory teaching experience is an important factor in Pharmacy students' learning experience. The students experienced a lowering of their learning outcomes when laboratory activities were changed to online activities as a response to the COVID-19 pandemic. An important reason seems to be the lack of opportunity and time for dialogue and the scaffolding of their learning through discussions with the teachers.

Students stressed the importance of the embodied experience as a key factor in their laboratory learning, and we found that the embodied experience provided students with ways of structuring their learning experiences temporally, by providing narrative or causal structures.

Producing and analyzing data themselves was conceived by the students to be an important element in the students' learning experience in the laboratory. We have argued, on the basis of Latour and Woolgar's[21] description of a research lab, that the teaching laboratory can be considered a site for production and transformation of texts aided by inscription devices. If the overarching aim of university laboratory teaching is for students to acquire familiarity with such transformations, then online activities where students are provided results to analyze may be considered a fairly poor substitute.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c01113.

Survey questions and interview guide in English translation (PDF, DOCX)

AUTHOR INFORMATION

Corresponding Author

Laura Teinholt Finne − *Department of Pharmacy, University of Copenhagen, 2100 Copenhagen, Denmark*; orcid.org/0000-0002-5015-7079; Email: laura.finne@sund.ku.dk

Authors

Bente Gammelgaard − *Department of Pharmacy, University of Copenhagen, 2100 Copenhagen, Denmark*

Frederik Voetmann Christiansen − *Department of Science Education, University of Copenhagen, 2100 Copenhagen, Denmark*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.1c01113

Notes

The authors declare no competing financial interest.

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Appendix 4 : Paper 4 – Pharmacy students' conceptions of theory-practice relation in the analytical chemistry laboratory – a phenomenographic study

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Pharmacy students' conceptions of theory–practice relation in the analytical chemistry laboratory – a phenomenographic study†

Laura Teinholt Finne, *[a] Bente Gammelgaard [a] and Frederik Voetmann Christiansen [b]

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In the undergraduate student laboratory teaching, one of the most common goals is developing improved conceptual understanding linking theory and practice. This study presents a phenomenographic analysis of pharmacy students' conceptions of the theory–practice relation in the laboratory. Through semi-structured interviews with pharmacy students about laboratory teaching and learning, we find that the students conceive the laboratory experience of the theory–practice relation in three qualitatively different ways. They perceive the laboratory experience as either (i) a visual representation of the theory, (ii) acting in a multimodal setting supporting theory, or (iii) as a complementary perspective in understanding theory. Furthermore, the conceptions were context-dependent and changed over time. We discuss how these three different perspectives may affect the students' learning outcomes and suggest how teachers can accommodate the perspectives in their teaching.

Introduction

Laboratory work has a central position in science education, especially in the chemical and pharmaceutical sciences. Many scientists and science teachers assign an important role to the practical work in the laboratory, and science educators see many benefits from students' practical work (Hofstein and Lunetta, 1982, 2004; Tobin, 1990; Hofstein and Mamlok-Naaman, 2007). The learning objectives claimed to be associated with laboratory work are practical skills, interest and motivation, problem-solving, application of scientific principles, and understanding of the nature of science (Hofstein and Lunetta, 1982, 2004). Reid and Shah (2007) summarise the goals for laboratory work in a chemistry setting as obtaining: skills relating to learning chemistry, practical skills, scientific skills (observation, deduction, and interpretation), and general skills.

Even though many intended goals for laboratory teaching have been proposed, the relationship between students' laboratory experiences and learning outcomes is still unclear (Hofstein and Mamlok-Naaman, 2007). A substantial critique of laboratory work was presented by Hodson (1993), who claimed that laboratory work is unproductive, confusing, and often used without clear goals and well-thought-through processes. With a broad range of goals for laboratory teaching, teachers need to clearly define the intended goals to avoid misalignment with students' expectations (Bruck and Towns, 2013; DeKorver and Towns, 2016; George-Williams *et al.*, 2018; Seery, 2020). In addition, there is still a need for more evidence of the relationship between student learning and laboratory experiences (Bretz, 2019).

A recent review of empirical studies (Agustian *et al.*, 2022) reported that student learning outcomes from laboratory teaching can be discerned within five clusters: experimental competences, disciplinary learning, higher-order thinking, transversal competences, and affective outcomes. The cluster of disciplinary learning involves conceptual understanding, theory–practice relation, and academic achievements (*e.g.*, grades). In the empirical studies, researchers reported improvements in students' understanding of theoretical concepts and the benefit of laboratory work in improving such conceptual understanding by connecting theory and practice (Agustian *et al.*, 2022). Furthermore, studies show that students highly value the laboratory for the possibility of connecting theory and practice (Boud *et al.*, 1980) and even more when lectures and experiments are closely linked (Borrmann, 2008).

Students' conceptions of science are closely related to their epistemic beliefs. In a seminal work from the '70s, Perry presents students' epistemic development over their college years (Perry, 1970). Perry developed a scheme that categorises students' epistemic beliefs in nine different positions further

[a] *Department of Pharmacy, University of Copenhagen, Denmark. E-mail: laura.finne@sund.ku.dk*
[b] *Department of Science Education, University of Copenhagen, Denmark*

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divided into stages, dualism (position 1–2); multiplism (position 3–4); relativism (position 5–6); and commitment in relativism (position 7–9). The college students scored an average of 2.4 in their first years and 3.2 in the last years in the Perry scheme, with the numbers referring to their position. This leaves many students in the dualistic stages when they enter college or university (Finster, 1989; Grove and Bretz, 2010). In a study reported by Mazzarone and Grove (2013), they investigated students' changes in epistemological beliefs over the first two years. Differences in the students' responses in the Chemistry Expectations Survey CHEMX (Grove *et al.*, 2007) were followed up with student interviews. From the interviews and the survey, it is evident that the students' experiences in the laboratory are of great importance for developing their epistemic beliefs. They highlighted the laboratory as the place where theory connected to the physical world. Going back to Perry's stage of dualism, one such dualism could be theory *vs.* practice. A central part of scientific activity is related to the representation of phenomena through theory, or conversely, experiments may serve to corroborate or illustrate the theory. From this perspective, the theory is foregrounded and the experiment is backgrounded – experiments are thought of as support for theoretical claims. However, in the interplay between theory and practice, there is another side of the scientific endeavour, a material and technological side, which is crucial in understanding how science develops. This happens in the interplay between the theory and the experiment. Ian Hacking describes this two-sidedness of science in his book "Representing and intervening" (Hacking, 1983). With a dualistic epistemic belief, students will perceive these two sides of science as separate entities. As students develop their epistemic beliefs, they will understand the interdependency of theory and practice. The students will move towards an understanding and appreciation of both the representing and intervening aspects of science and how they interplay. Hacking describes the notions of representing and intervening in this way: "We represent in order to intervene, and we intervene in the light of representations" (Hacking, 1983, p. 31).

The theory–practice relation is prevalent in teachers' descriptions of goals for laboratory instruction and is also present in students' learning outcomes of laboratory work (Reid and Shah, 2007; Bruck *et al.*, 2010; Bretz *et al.*, 2013; Bruck and Towns, 2013; Galloway *et al.*, 2016; George-Williams *et al.*, 2018). However, the argument for teaching theory in the laboratory does not have a substantial claim according to Hofstein and Lunetta (1982, 2004). Seery (2020) further raises the question that even if there is evidence for learning chemistry theory in the laboratory, why would we choose one experiment over the other? Is some theory or concept more important than the other?

We want to investigate students' conceptions of the theory–practice relation to elaborate on how students conceive the theory–practice relation in the laboratory in an undergraduate context. Therefore, we aim to answer the research question:

– "What are the different ways in which 2nd year pharmacy students experience the role of the practical laboratory work in the theory–practice relation?"

Theoretical background

Students' differences in conceptions of learning are interesting because many have suggested and found correlations between students' conceptions and approaches to learning and learning outcomes (Trigwell and Prosser, 1991; Ramsden, 1999; Richardson, 2005; Ullah *et al.*, 2016).

In this study, we apply the research approach of phenomenography. The object of a phenomenographic study is the variation in experiences of a phenomenon in a certain group (Marton and Booth, 1997). The underlying assumption is that there is a limited number of qualitatively different ways of experiencing a phenomenon. In this study, the phenomenon is the role of the laboratory in the theory–practice relation. The outcome of a phenomenographic study is a description of the different ways of experiencing the phenomenon, also called categories. The focus in these descriptions is on the relational differences between the categories.

Phenomenography has been widely used in higher education contexts but has not yet been widely used in the study of laboratory education. A few recent exceptions are Burrows *et al.* (2017), who investigated students' perception of project-based learning in organic chemistry, and Chiu *et al.* (2016), who explored students' conceptions of learning science by laboratory work. Chiu *et al.* described six different categories of students' conceptions of learning science by laboratory: memorizing, acquiring manipulative skills, obtaining authentic experience, examining prior knowledge, reviewing prior learning profiles, and achieving in-depth understanding. Some of these categories relate to the student's experience of theory–practice relation, but it was not a specific focus in that study.

Students' experiences differ from their different intentions or purposes in a given context. The focus of their awareness may therefore differ and lead to qualitatively different ways of experiencing phenomena. From the phenomenographic perspective, experience and learning rely on two components of conscious awareness – the referential aspect and the structural aspects. The referential aspect is concerned with the meaning of the experience – *e.g.*, quantitative determination of a drug as part of quality control. In contrast, the structural aspect is concerned with the individual parts of the experience and their relationship, *e.g.*, the different parts of the exercise (Marton and Booth, 1997; Han and Ellis, 2019). The structural and referential aspects are always present in experience, but the experiences differ depending on the student's focus of awareness (Marton and Booth, 1997, p. 87). This framework has been defined and used with great variation (Harris, 2011). In this study, we use the framework to describe critical aspects distinguishing the categories of conceptions from each other (Collier-Reed and Ingerman, 2013). A learning process always involves "what is being learned" and "how is it being learned". These questions can be considered in terms of meaning and structure, and we may consider what students learn about the theory–practice relation, both in terms of the meaning they ascribe to the relation and the way they understand the context and constitution of the theory–practice relation.

Method

Data collection

The empirical data consist of 30 semi-structured interviews with students from the pharmacy program at the University of Copenhagen (UCPH). The students were interviewed at the beginning of the semester (16) and shortly after the exam (14).

The students were presented with the research project during a lecture in the course Pharmaceutical Analytical Chemistry. They were asked to fill out a short questionnaire and volunteer for the interviews by ticking a box. Ninety-six students (of a cohort of 237) answered the questionnaire (see the ESI†). Twenty students volunteered for the interviews. However, due to unresponsiveness and withdrawal, only 16 students were interviewed. Based on the questionnaire, the student sample appeared representative of the broadness of the student population based on the number of classes passed, previous school background, and self-assessment of their performance and experience in the laboratory. However, in qualitative research, saturation in the data indicates the quality of the sample. There is no ''one size fits all'', when it comes to saturation in qualitative methods. Fusch and Ness (2015) describe saturation as rich (quality) and thick (quantity). The interview guide secured rich answers from the students within the themes. Regarding thickness, we were limited by the number of students volunteering to participate. However, we experienced during the coding of the interviews that even after a few interviews, no new themes emerged, and we take this as a sign of saturation.

The course is compulsory 7.5 ECTS‡ in the 4th semester of the bachelor program and includes 72 hours of laboratory work (18 × 4 h) and 19 lectures (45 min) supplemented with videos and quizzes. Students work in groups of 2–3 in the laboratory and hand in reports as groups and receive feedback on the reports in the laboratory. The course is based on instrumental analytical chemistry including liquid and gas chromatography (LC and GC) with spectrophotometry or mass spectrometry detection. The exercises include observing the influence of changing instrumental parameters, sample preparation, calibration methods, and critical data analysis. They are closely related to the quality evaluation of pharmaceutical preparations. Students prepare protocols for analysis based on pharmacopeia standards, execute the quantitative analysis and evaluate the result. The laboratory work is evaluated as passed/failed based on reports including study questions. Furthermore, a 3 h written examination is assessed by grading. This exam is closely related to the calculations and study questions answered in the reports. However, in a previous study, we found that not all students conceive that there is a strong connection between the laboratory work and report writing and the final exam (Finne *et al.*, 2021). The central learning objectives for the course are to obtain an overview of principles and application of pharmaceutically relevant analytical methods, to transfer a given pharmacopeia standard to a work plan, perform the analysis, critically evaluate results and uncertainties, and report data. Due to the pandemic of COVID-19, the students only completed half of the laboratory course on campus. The remaining part was completed by making the same reports as under 'normal' circumstances, based on handed-out data sets rather than their own data, and with the help of a few explanatory videos. The assessment form was not changed as a result of the pandemic.

The interview guides were based on the congruence model from Hounsell and Hounsell (2007), describing six areas of congruence important for developing ways of thinking and practicing for high-quality learning. The six congruence areas are students' background and aspirations, course organization and management, teaching activities, assessment and feedback, learning support, and curriculum aims, scope, and structure. The guides were developed to cover all of the six congruence areas through the following themes:

The focus of the first interview:
– Previous experiences with laboratory work
– Aspirations and reasons for studying pharmacy
– Role of laboratory teaching for their learning

The focus of the second interview:
– Experience of laboratory *vs.* lockdown ''online'' version
– Preparation for the exam and experience of the exam
– Experience of learning outcome

Usually, the interview guide in a phenomenographic study is more open than we describe it here. We acknowledge that this is a deviation from more traditional phenomenography. We used the congruence model as a scaffold and as guidance in the interviews since it covers important aspects of the experience of quality learning. Thus, we use the congruence model to focus on the phenomenon of quality learning in the laboratory. All interviews were recorded and transcribed verbatim. All students had given informed consent to participate according to the GDPR rules.

Data analysis

Based on reading and re-reading the transcripts, the first author comprised a condensed profile for each student, and important sentences were noted. The overall emerging themes were discussed based on selected full transcripts and the profiles. Students were only explicitly asked about their background and aspirations. Apart from this, four overall themes emerged from the initial analysis: (i) students' experiences of what it means to understand, (ii) students' experience of theory–practice relation, (iii) students' experience of the learning process throughout the course, and (iv) the role of affective factors. These additional themes arose from the focus points in the interviews but are analytical constructs.

The present study focuses solely on the theory–practice relation. Similar statements from this theme were grouped and initial categories were formed: the lab as help to remember, verify understanding, verify knowledge, or experience differences. Statements aimed at representing the variation and distinctness in each category were identified (first author) and checked against the full interview to verify that the interpretation was

‡ European Credit Transfer System – 60 ECTS correspond to 1 year full-time studies (1640 h), 7.5 ECTS equals 205 h.

representative and true to the students' experience. The final categories were described with a focus on differences in students' experiences and refined through several iterations. Following this, the students' conceptions were coded based on their profiles. The categories are described on the collective level, meaning that individual students may express more than one conception.

A dialogic reliability check was applied by discussion and agreement on the categorization (Åkerlind, 2005). In a dialogic reliability check, the researchers discuss and critique each researcher's interpretive hypotheses and find a mutual agreement based on this discussion. This method was selected over an interrater reliability measure, which is becoming more common in chemical education research (Watts and Finkenstaedt-Quinn, 2021). However, an interrater reliability check may be quite uninformative as categories are described on the collective level, individual statements cannot entirely express the category and some statements may express traits from more than one category (Sandbergh, 1997).

Results

The phenomenographic analysis of the data shows that the students display three different conceptions of the laboratory experience concerning the theory–practice relation:

A. The laboratory experience as providing a visual representation of the theory,

B. The laboratory experience as acting in a multimodal setting supporting theory, and

C. The laboratory experience as providing a complementary perspective in understanding theory

In the following, we rely on the students' use of the word *theory*. It is clear from the interviews that the terms "theory" and "theoretical" refer at least to the concepts and models described in textbooks and discussed in lectures but are sometimes also the theoretical descriptions found in protocols of the experiments. In the interviews, "theory" is often contrasted with "practice" which describes work done in the laboratory, especially related to the execution of experiments and manipulation of instruments and chemicals. Quotes from students are marked with DXX-X where the first two xx is the participant number; these are unique to each student. The number after the dash is 1 for the first interview and 3 for the last. For some students, there is an interview in the middle marked with 2. This round of interviews was conducted as a response to the lockdown but is not a part of this analysis. Findings from the second round of interviews are reported elsewhere (see Finne *et al.*, 2022)).

Conception A – the laboratory experience as providing a visual representation

When the students express the conception of the laboratory experience as a visual representation of the theory, they focus on the close similarity between theory and practice. They describe the theory as general expressions of concepts and phenomena and the laboratory experiments as illustrations or instances of specific situations of the general theory. Thus, the laboratory experience exemplifies the knowledge the student has already encountered in theory. The students use the visual representation from the laboratory to improve their understanding and aid in recalling the theory and concepts.

Several students express that they are visually oriented in their learning, probably referring to individual learning styles (see *e.g.* (Dunn and Dunn, 1978; Stone, 2021). This is exemplified in the following quotes where the students express a clear understanding of themselves as a "picture-person" or as being very "visual". The laboratory stimulates their visual sense as they observe instruments and reactions, which helps them to make sense of the theory and concepts. "*My brain needs a picture of it before I can understand it. Especially because I'm very much a 'picture-person' so my memory more easily remembers things if it is in picture form [...] compared to something I have read because I forget that.*" *D11-3 – June 2020*

"*all sorts of people have written this and all sorts of people have said that... but can I SEE it? I'm very visual so if I can see things and imagine them in my mind then it makes sense to me. But, reading a text without pictures or illustrations – it just disappears completely. I catch nothing of it... completely ... well it comes in through the eyes, but [apparently] exits again through all other holes. Because it does not stick anywhere.*" *D05-1 – February 2020*

Furthermore, the images the students visualize are more realistic and detailed when they have experienced the reactions and instruments in the laboratory: "*I also feel that when we've been to the analytical chemistry lab and have read about the different instruments... to actually see it, to get the instruments opened and see: 'Okay, this is what it actually looks like'. And sometimes it is completely different from what you imagined when you sat at home and read in the book.*" *D16-1 – February 2020*

Thus, from this perspective, the laboratory experiences provide a visual representation of theory, a collection of visual images strengthening the understanding of the theory–practice relation. This conception expresses a "passive" approach to laboratory work, as it mainly focuses on how the laboratory experience provides images or pictures that may aid in understanding the theory but does not describe the students own engagement with the apparatus or the process. The students emphasise the representational aspect of science in Hackings understanding of representing and intervening.

Conception B – the laboratory experience as acting in a multimodal setting

Students with this conception of the laboratory experience emphasize that it is a "whole body experience" with all senses in use, not just the vision. Moreover, the conception stresses the action part of the experience – the laboratory experience is not just about acquiring a different image or representation but also about doing or acting in the laboratory setting. Thus, students emphasize the importance of "doing it themselves" or "having it in your hands". They focus on creating their own data and taking ownership of the data produced. They experience the laboratory as a place to experience phenomena and correct their own misinterpretations of the theory. They conceive the laboratory experience as acting in a multimodal setting, where they create their own understanding of the theory supported by the embodied experience.

In one interview, the interviewer asked the student why the experiment could not be watched on a video instead:

"Well, I guess you might do that, but I don't think it would have the same effect. I'm not quite sure why, I just don't think so... I think it is something basically human in some way...being there physically. Now, I lift this cup, and there is a chemical in it and I put that into a bottle... quite fundamental" D01-3 – June 2020

The students' action plays a role in the construction of knowledge. Their understanding of how the knowledge was created improves due to their active role in establishing it: "*this machine spat out this chromatogram so ... well, it doesn't come from nothing! It is not just some scientific article they [the teachers] have printed and said: "now, let's look at this chromatogram, that is probably right". You know for sure that this is your own data, you know, it is something you created yourself. It's not just some numbers someone made up." D05-1 – February 2020*

Several students describe that the laboratory experience makes theory, data, and experiments more real, as opposed to what is "in the books". This certainly does not imply that they consider what they read as being "fake". Instead, it refers to them being active in the construction of the knowledge, which makes the theory more relatable. When they can reproduce the theory and use it in the laboratory, they take ownership of the knowledge – they learn about theory through practice, and the theory enables them to understand how to act in the lab: "*It gives me so much more when I have it between my hands. Everything suddenly connects when I read as well and then... when I'm in the lab then... 'ah, okay, I do this because of that. It just clicks together differently, I think." D03-1 – February 2020*

The students who conceive the laboratory experience as acting in a multimodal setting show an active approach to the laboratory work. Through their action, they collect the experiences of theory and practice relation. As in conception A, they focus on the similarity or compliance between the laboratory experience and the theory. The students have begun to grasp the importance of representing as well as intervening, though they have yet to understand how these two aspects of science interact and interplay.

Conception C – the laboratory experience as a complementary perspective

When the students experience the laboratory as a complementary component, they focus on the differences between the theory and the practice. They acknowledge that theory and practice are complementary and describe the experiences they cannot obtain from reading textbooks or manuals. They emphasize the importance of observation and actively acquiring practical skills in learning about the technologies, the chemical entities, and the reactions. "*I think it is the practical aspect. One thing is to read about a method 100 times, another is to actually perform a titration [...]. The first time we did that it was so much more difficult than what we had read in the manual. 'well, you add something dropwise until it changes colour', but that is pretty abstract [...] how much of a colour change do you want? Do you want dark magenta or a bit lighter? [...] Such a thing as weighing. It sounds simple enough to pour something and get the exact decimals, but there is often much more to it. Well, you have to remember to close it [the analytical scale] because the air can interfere, and well... stuff like that. I think, there is so much you just didn't get from the theory, however, as soon as you were in the lab you learned it." D03-1 – February 2020*

The point, that the laboratory work by itself does not necessarily reveal the relation to theory, is highlighted by students who express that the practical work in the laboratory can be completed without understanding what you do: "*Yes, you can perform many of the steps, even without the understanding of it because it is like a baking recipe. Then you just add this and do that and that. But, if you don't get an understanding of it, then you cannot bring it with you." D04-1 – February 2020*

In this way, the student underlines that the complementary relationship between theory and practice forms the understanding and the skillset needed for future applications. Students also focus on the importance of experimental circumstances. They experience that the experiments are more complex and complicated than the impression given in the theoretical description and that the complexity adds to the understanding:

"Some things you just can't get from reading [...] of course you can refer to the theory. But you can't, as far as I'm concerned... I wouldn't know where to look about all the practical stuff. 'How are you supposed to do this?', and 'what if the machine says like this?' Well, all those sorts of things are impossible to find. And you wouldn't be able to ask about those things [when not in the lab], and it's really valuable." D02-3 – June 2020

One student described the experience as building a "data center" that collects the experiences and forms a knowledge base from the laboratory work that enables the relationship to theory. The "data center" builds expertise, or intuition. You learn from mistakes and realise that the theory alone does not reveal the whole picture: "*You get a feel for it. You get some sort of – you gain a kind of .... data center, or... You just get a lot of data about how things work that you don't get from the books. [...] There are a lot of things you may have missed out on, and such. [...] You might think: 'yes, that's probably fine', and then when you've tried it in the laboratory, then you find that the solution is not at all in solution. It is filled with particles, and it is obvious to everyone that of course, you should have filtered it. And you are like: 'How was that obvious for anyone?' [...] But then you got to see it, and you got to do it, and then when you read it afterward you could actually understand that of course some compound was formed that just had to be removed. It just wasn't obvious before you had tried yourself" D05-1 – February 2020*

This student continues in the second interview to describe how the small details that can go wrong in the laboratory, make you reflect – a practical perspective that is absent in the theoretical descriptions: "*When you read a USP [U.S. Pharmacopeia] at home and think about how and what you want to do, then no* *mistakes happen. None of those weird uncertainties happens [...] what if it is not in solution after 10 minutes? [...] will it tamper with the sample if you do it [sonicate] for too long? All of these thoughts are left out. It is not something you think about when you just read at home. [...] all those small things that can go wrong [...] in the lab there is always something. [...] You get to think about all sorts of things you would not have thought about if you just sat at home because there would not have been a problem. [...] You can't take that experience with you when you haven't been in the laboratory.'' D05-3 – June 2020*

Making mistakes in the laboratory triggers reflection on the student's present knowledge and considerations on the practical handling of samples and the causes of failures. ''*Things go wrong if you do not do it properly and then you get to try to explain yourself why [...] in practice it is just different because there are so many parameters you have to take into consideration [...] those human errors. 'When do they happen?' 'What do they mean?' [...] An example could be the first time we did MS spectroscopy, there was just something that puzzled us. It would not make sense. [...] could it be this? Or that? [...] you always have to figure out what went wrong? Why? And what can we do to prevent this the next time?'' D06-3 – June 2020*

The students who conceive the laboratory work as providing a complementary perspective to theory acknowledge the active approach to the laboratory and the use of different senses and modalities of learning. Still, unlike the two other conceptions, they focus on the differences between theory and practice and how the two complement each other. This is a crucial starting point for the students' understanding of the interplay between representing and intervening that Hacking describes.

Discussion

Critical aspects of the referential and structural aspects of conceptions of theory–practice relation

In this study, we find that students present three qualitatively different ways of understanding the role of the laboratory in theory–practice relations. The conceptions A, B, and C above are described in that order to show an increasing sophistication of the student's understanding of the theory–practice relation. Two critical aspects of the theory–practice connection appear from the three different categories. One aspect considers the students' focus on active or passive engagement with the laboratory experience. This we call the referential aspect of the experience. The students either create meaning without engagement leading to conceptions of the laboratory as a representation of previous known theory (passive) or through engagement with the material in experimentation (the active perspective). The other critical aspect is related to the structural aspect of experience. It concerns the students' focus either on the similarity and compliance of theory with practice or the differences between theory and practice.

Concerning the referential aspect of the passive *versus* active approach, all students are of course active and perform diverse manipulative and procedural steps in the laboratory setting.

Table 1 Schematic representation of relational differences between categories

Conception	Referential aspect	Structural aspect
A	Passive mental engagement	Focus on similarities
B	Active mental engagement	Focus on similarities
C	Active mental engagement	Focus on differences and whole

However, according to their statements, the meaning-making part of the laboratory experience is quite dependent on the situation. When students express the passive approach they experience that the ''theory'' manifests itself in a phenomenon they observe or see in the laboratory, whereas students having an active understanding of the meaning-making process in the laboratory describe how they have been involved in the processes and created meaning by engaging with the phenomenon. Concerning the structural aspect, the students focused on either compliance with the laboratory experience with theory or conceiving the laboratory experience as providing complementary experiences to their theoretical understanding. A schematic presentation of the three categories is shown in Table 1.

The students' conceptions of theory–practice relation form a hierarchical structure going from a more passive conception focusing on a visual representation of theory to B focusing on doing the experiments themselves in a multimodal setting, and finally, a conception highlighting the complementary nature of the relationship between practice and theory.

Students expressing conception A are very focused on pictures provided in the laboratory setting and the visual sense. They often use the term ''see'', but it is difficult to interpret from the interviews whether the term is meant literally or is used as a metaphor for understanding. At least in western countries, sight is perceived as the most important of the senses (Majid *et al.*, 2018). This may explain why conception A is so distinctly focused on the visual sense. We have placed conception A – the laboratory as a visual representation – lowest in the hierarchy of theory–practice relations. This is following other taxonomies such as Blooms, where the two lowest levels of understanding, remember and understand, are often associated with verbs related to the visual sense such as *trace, outline, point, match, identify* and *visualize, observe*, respectively (see *e.g.*, (Shabatura, 2014). Furthermore, with this way of conceiving the theory–practice relation, students limit their awareness to focus on the similarity or identity between theory and practice and how the laboratory experience can inform their theoretical understanding.

Students with conception B focus on creating and doing the experiments themselves. The focus on *seeing* is less pronounced, and there is a focus on *doing* and actively participating in the experiment. The experience in the laboratory is centered on the embodied and active experience (Hardahl *et al.*, 2019). Thus, the experience of getting the instrument working, being physically present in the laboratory, and playing an active role in creating the data plays a significant role. The same important insight was obtained by Dukes (2020) when reflecting on how to teach an instrumental analytical chemistry course during the COVID-19 pandemic. He found that the waiting time and manipulation of the instruments are essential for the students' experiences of engagement with the data afterward. So, when it comes to practical work in the laboratory, learning simply ''to see differently'' might be a bit simplistic since the experience has an important embodied dimension.

Another way of understanding the distinction between conception A and conception B and C is by relating them to Ian Hacking's description of two central objectives of science: representing and intervening. In the interviews, conception A foregrounds theory by seeing the laboratory experience as a (visual) representation of the theory. Thus, it emphasises theory in the theory–practice relation. Conception B moves beyond representing intervention by stressing how the laboratory experience is also crucially an experience of acting in a physical and technological environment. And conception C goes further by recognizing that the relationship between theory and practice is not a question of seeing examples of theory in practice, but rather recognizing the strong connection between them. An example could be the development of observational skills. Of course, observations are conditioned by our theoretical expectations, and if the students do not have any expectations beforehand, they will not know what to observe (Johnstone and Al-Shuaili, 2001). Hence, theory or some sort of expectation is an important prerequisite for going into the laboratory, but observations also rely on equipment and how that equipment works (Hacking, 1983, p. 230). Understanding what it takes to get the equipment running is a focus in conception C. As Hacking puts it: ''[...] A laboratory course in which all the experiments worked would be fine technology, but would teach nothing at all about experimentation'' (Hacking, 1983, p. 230). These theoretical elaborations match well the gist of what is expressed by the students who represent conception C in the interviews.

Considering the different perspectives students express on the theory–practice relation, teachers' perspectives, when they refer to the theory–practice relation in laboratory learning, become interesting. For example, in a large qualitative study on students' and teachers' understanding of aims for practical chemistry courses (George-Williams *et al.*, 2018), it was found that first-year students tend to focus more on the theory–practice relation compared to upper-level students, who instead focus more on experimental design and the manipulative skills (George-Williams *et al.*, 2018). Furthermore, their study observed that many of the goals described by the university teachers were rather simplistic, and they suggested that teachers discuss their views on the aims of laboratory teaching. Thus, the ''theory–practice relation'' may be referred to by students and teachers without considering what it means. This can be a problem if the way we assess laboratory work is likewise promoting a simplistic conception of the relation. When this happens, is it perhaps also because the theoretical understanding is easier and cheaper to assess compared to a broader range of laboratory competences?

Implications

The finding that students hold different conceptions of the laboratory's role in theory–practice relation and identifying the referential and the structural aspects that make the different conceptions distinct may be used for course developers. Changing the context during a course may change students' conception toward a more active referential approach. More research on which changes could move the students to the more elaborate conception C is needed. We would suggest looking at the influence of the exam on the students' conceptions, the openness of the laboratory instruction (Domin, 1999) or the effect of the teachers' or teaching assistants' conception of theory–practice relation. It is very conceivable that other teaching contexts would lead students to express other or additional conceptions of the theory practice relation.

As students have different conceptions of the theory–practice relation, the same could be the case for teachers. Therefore, a similar investigation of teachers' conceptions would be interesting. We know that teachers' conceptions of learning affect students' conceptions (Richardson, 2005). Hence, alignment of teachers' and students' perceptions of the theory–practice relation is important. As the term theory–practice relation is one of the most prominent learning outcomes in course descriptions, studying the different perceptions of the theory–practice relation among teachers, in a course or even curriculum or department would probably be beneficial for the learning outcomes.

A general encouragement to reflection and discussion among teachers on the meaning of the theory–practice relation could lead to more specific descriptions of this concept in higher education laboratory education. Eventually, this term could be replaced by more detailed descriptions in the individual courses. We encourage teachers to carefully reflect upon the theory's emphasis in laboratory courses. We suggest more focus on the practical aspects and the tacit embodied dimensions of laboratory experiences may promote different types of learning outcomes from theory and practice.

Limitations

Data on the student grades have not been collected. Hence, we cannot comment on the relation between students' achievement and their conception of the theory–practice relation. Furthermore, as our recruitment took place *via* a lecture with only half of the students present, we recognize a certain sample bias as the type of students who volunteer to be interviewed may not be representative. Due to COVID-19, the students experienced a lockdown halfway through the laboratory course, and the situation likely affected the students' experiences.

Conclusion

This study shows that students in the course Pharmaceutical Analytical Chemistry express qualitatively different experiences of theory–practice relations. We find three different conceptions A, B, and C. The conceptions are ranged hierarchically, with conception A as the least sophisticated and conception C as the most sophisticated. Conception A describes the laboratory experience as a visual representation of the theory, and how the visual impressions from the laboratory experience help the students to memorize the concepts and theory. Conception B describes the laboratory experience as acting in a multimodal setting supporting theory acquisition by following procedures, interacting with instruments, and being involved in creating data. The students perceive the laboratory as a place for doing chemistry that helps them relate to the theory, and the bodily experience supports their engagement in theory and concepts. Conception C describes the laboratory experience as a complementary perspective to understanding theory. The students highlight the learning gained from making mistakes and dealing with problem-solving from unideal situations.

Two different critical aspects emerge from the analysis. The referential aspect concerns how students focus their awareness. This is divided into a passive approach where students describe their learning experience in terms of passive observation of the phenomena and an active process where students describe their learning experience in terms of the laboratory actively giving meaning to the theory by intervening with the phenomena. The structural aspect concerns students' focus on the laboratory experience as confirmation of or compliance with the theory in contrast to perceiving the experience as complementary to the theory. The conceptions were dependent on context and students might change conceptions over time.

Conflicts of interest

There are no conflicts to declare.

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